F-30.10

FINAL REPORT

ON

A VISUAL OBSERVATION INSTRUMENTATION SYSTEM

FOR

THE LUNAR ORBITER

PREPARED UNDER CONTRACT P. R. 950004
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Under the Direction of

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1.0 INTRODUCTION

This report covers work done during the period September 1, 1960 through December 31, 1960, and is the final report on the Visual Observation Instrumentation System study contract.

The bulk of the report is contained in sections 4 and 5 which cover respectively a Parametric Study and a description of two Exemplary Systems.

The Parametric Study contains a large number of curves graphically illustrating the more pertinent interrelationships of the many variable parameters. A cursory examination of these curves indicates the feasibility of extracting a number of workable systems. However, a careful weighing of the far reaching effects of the variation of any one parameter frequently shows that its range must be quite restricted. Based on such a weighing the two systems described in section 5 have been derived. Although it is clearly impossible to produce finished designs at this time, it is the conviction of the authors that both systems are entirely feasible and represent near-optimum designs.

It should be emphasized that before the Parametric Study could be analyzed and the effects of parameters on system performance evaluated, it was necessary that criteria of goodness be established. These, in turn, were dependent upon a fundamental understanding of the mapping problems in terms of the constraints imposed by nature and of the end use of the system output.

The Problem and the System Philosophy are discussed concisely in sections 2 and 3 of this report. Although not specifically included in the Study Work Statement, the ultimate cartographic problem continually insinuated itself into the search for criteria by which to judge system performance. Consequently, some study of this area was mandatory and a discussion of the general problem of mapping the lunar surface is included in Appendix D.

2.0 STATEMENT OF THE PROBLEM

2.1 GENERAL

Qualitatively, the problem at hand consists in defining the optimum photographic and electronic package (VOIS) for collecting, from a selenocentric satellite, the data necessary to the preparation of a topographical map of the entire lunar surface. A second, but at least as important, requirement is the collection of high resolution data from selected areas of the surface in the interest of identifying possible future landing sites.

2.2 LUNAR PARAMETERS AND ORBITAL CONSIDERATIONS

The above statement is comprehensive and correct, but because of its brevity it is deceptively simple. A more complete statement of the problem must contain a description of the environment and other constraints and conditions under which the system must operate.

Certain of these constraints are a result of satellite state-of-the-art while others are fundamental in nature and cannot become subjects of compromise. A list of the most significant of these latter follows:

Lunar Diameter	3480 KM
Lunar Circumference	10,910 KM
Lunar Area	38.2 x 10^{12} square inches
Sidereal Period	27 days, 7 hours, 43 minutes, 11.5 seconds (2,360,580 seconds)
Elipticity of Lunar Orbit	0.055 (1900 epoch)
Lunar Apogee	252,948 miles
Lunar Perigee	221,593 miles
Lunar Surface Gravitational Field	0.165G
Incident Solar Illumination	13,000 foot-candles
Albedo	0.07
Surface Brightness	910 foot-lamberts
Angle between Ecliptic and Lunar Orbital Plane	5°
Angle between Ecliptic and Lunar Equatorial Plane	1.5°

Angle between Lunar Orbital Plane and Lunar Equatorial Plane	6.5°
Dates of Lunar Equinoxes	July 31, 1962 and January 20, 1963
Lunar Satellite Period (seconds)	$0.0899\ R^{3/2}$

where R = distance of satellite from center of moon in KM

The significance of some of the above constants is not immediately obvious, but they have all entered into the study as well as many of their combinations and derivatives. For example, it is necessary that the experiment take place during a period containing a lunar equinox in order to ensure both poles being illuminated at some time during the month of operation.

Appendix E contains a discussion of the manner in which these natural constraints affect the system operation and a schedule showing relative operational times of the several sub-systems.

Certain other facets of the problem are more or less under the control of the designer and these are treated at length in section 4.0. Figure 4.1 illustrates the degree to which the choice of one parameter, in conjunction with the natural geometry exerts an influence on all parts of the system. Thus the specification of altitude fixes the period, the walk distance, the ground velocity and the number of periods per month. These, in turn affect focal length, resolution, bandwidth, primary power, etc.

The most significant general man-made constraint is that imposed by the booster power plant available at the experimental period. This determines the weight and size of the payload, the available power, the transmitter power, the bandwidth and finally the ground resolution. This area is again examined in detail in section 4.0.

The second stringent artificial requirement involves the desire to avoid contamination of the lunar surface by earth organisms. Thus all VOIS components as well as the complete package must undergo a sterilization procedure. A major facet of the problem consists in the selection of a system which will emerge from this procedure unscathed.

Finally the best conceivable system becomes worthless if it fails under the stresses imposed by the environment of space. The VOIS package must experience and operate under extremes of temperature and very low pressures. It must withstand extreme accelerations and must operate in free fall, and it must pass through the radiation bombardment of the Van Allen belt and survive to perform its delicate function of providing mankind with a map of the moon.

3.0 SYSTEM PHILOSOPHY

3.1 GENERAL

Classically, a philosophy is the set of principles and criteria which govern the pursuit of an objective. As such, the VOIS system philosophy is dictated primarily by the statement of the problem and, like that statement, can be expressed in a brief generality. However, as all areas of the problem are examined, these generalities yield to specifics; principles and criteria designed to produce an ideal system are modified to provide an optimum realizable system; and only after the job is finished can the guiding philosophy be completely expressed.

At this point in the evolution of the VOIS package many fairly general conclusions may be reached. Some of these follow:

1. Provisions must be made to utilize the system to the fullest extent compatible with the natural constraints. This means that data will be transmitted at full permissible bandwidth at all times when LOS exists. (LOS means Line Of Sight)

2. The cartographic camera will provide full stereo information and will have a resolution of 10 to 30 meters depending upon a more definite establishment of its end use and the quantity of high resolution information required.

3. Resolution of the high acuity camera will be 1 meter.

4. An optimum compromise between undesired photographic redundancy and undue complexity has been reached.

5. The system will be all-electronic, mechanical motion will be minimized, and storage will be on magnetic tape.

6. Reliability is of paramount importance. Transistor circuitry will be employed wherever feasible and any areas of questionable reliability will be completely backed up by redundancy.

7. On a par with reliability is the necessity for the maintenance of schedules. This contractor is acutely aware of the danger in a program of this magnitude that one of the contributors will fail to meet his schedule, thereby nullifying the work of all.

Although subsequent sections of the report contain discussions of specific camera design for the fiber optic sensors, a general discussion of camera philosophy is pertinent and is therefore included in this section.

3.2 VOIS CAMERA SYSTEMS GENERAL

The purpose of this discussion is to establish general concepts of system design that are pertinent to realistic cameras that satisfy the objectives of the lunar orbiter program. Some knowledge of the order of magnitude of the potential parametric for possible camera configurations is necessary. Therefore reference is made to some conclusions of the parameters study. This is necessitated because the philosophy of design will vary significantly between, for example, cartographic cameras having a lens focal length of 50mm and reconnaissance cameras having 12 meter focal length lenses.

From the parametric study it becomes apparent that the cameras required should be operated at an altitude around 100 KM. The surface resolution for the cartographic camera should be from 10 to 30 meters hence lens focal lengths will range from 4 to 12 inches. The high acuity camera should have a surface resolution of approximately 1 meter, requiring a focal length of 120 inches. With these basic parameters we now know the framework into which these potential cameras must be designed.

Lunar Environment

Several conditions exist in the lunar environment that actually facilitate the design of the high acuity and cartographic cameras. These advantages are directly attributable to the lack of atmosphere. Consider the situation of photography through the total earth's atmosphere. The incident sunlight at the top of the atmosphere is approximately 13,000 foot-candles. This light is attenuated and scattered in passing through the atmosphere so that approximately 8000 foot-candles of direct sunlight reaches the surface. Some of the direct sunlight which is lost in traversing the atmosphere is scattered to produce atmospheric illumination or skylight. This contributes an additional 2000 foot-candles to illuminate the surface. Therefore the total surface illumination is approximately 10,000 foot-candles. The reflectance of typical earth surface detail ranges from 1 percent to 40 percent so that the brightness of ground detail ranges from 100 to 4000 foot-lamberts or has a contrast ratio of 40:1 at ground level. This light in passing back through the atmosphere to the camera will be attenuated and will have the scattered skylight added to it. Therefore the light reaching the top of the atmosphere will range from approximately 2060 to 4460 foot-lamberts. The contrast ratio has decreased from 40:1 at the earth surface to 2.16:1 at the top of the atmosphere.

The over-all lighting has been raised by approximately 2000 foot-lamberts by back-scattering. In addition to the very severe loss of contrast due to attenuation and back-scattering, the ultimate resolution has been decreased significantly by atmosphere turbulence. On the moon however, with the lack of significant atmosphere, the resolution loss due to turbulence and the absorption and back-scattering degradations are missing. The initial 13,000 foot-candles is incident upon the lunar surface (plus earthshine depending upon earth phase). Using a reflectance range of 0.047 to 0.18 results in a surface brightness of from 612 to 2340 foot-lamberts. This gives contrast ratio of 3.8:1 with no turbulence degradation. It is a known event in lens and mirror design that resolution suffers as the contrast ratio decreases. The current state-of-the-art in lens and mirror design is such that terrestrial systems are now atmospheric turbulence limited rather than diffraction limited when operated at high altitudes. In conclusion, the absence of lunar atmosphere allows us to obtain better operation from optical systems, especially those approaching diffraction limits.

Angular Field Of View

Due to the extremely small angular field of view required for the high acuity camera (2.5° at 100 KM vehicle altitude) one can contemplate the use of modified Petzval or Cooke triplet lenses or a Cassegrainian reflector system. These units may be designed to approach diffraction limits for narrow angles of view. They have however a curved focal plane which makes them unsuited for wider angle photographic film applications. The fiber optical sensor unit however may be readily countoured to match the curved focal plane thus eliminating the need for heavy field flattener lenses. The systems mentioned are apochromatized to decrease secondary color degradations.

Sterilization

One problem incumbent upon all camera systems is the sterilization requirement. Units containing organic lens cement will not withstand temperatures in excess of 70 degrees to 80 degrees centigrade. It is possible that air gap lenses requiring no cement could be designed. However other successful sterilization techniques are currently used for lenses. These consist of exposure to ethylene oxide gas or subjecting the lens to radiation. If the level of radiation does not exceed 10^6 Roentgens the glass will not discolor. If sterilization radiation values in excess of this are anticipated the lenses might have to be constructed of special non-discoloration glass. This constitutes a major redesign of lens elements if different glass is used due to refractive indices problems.

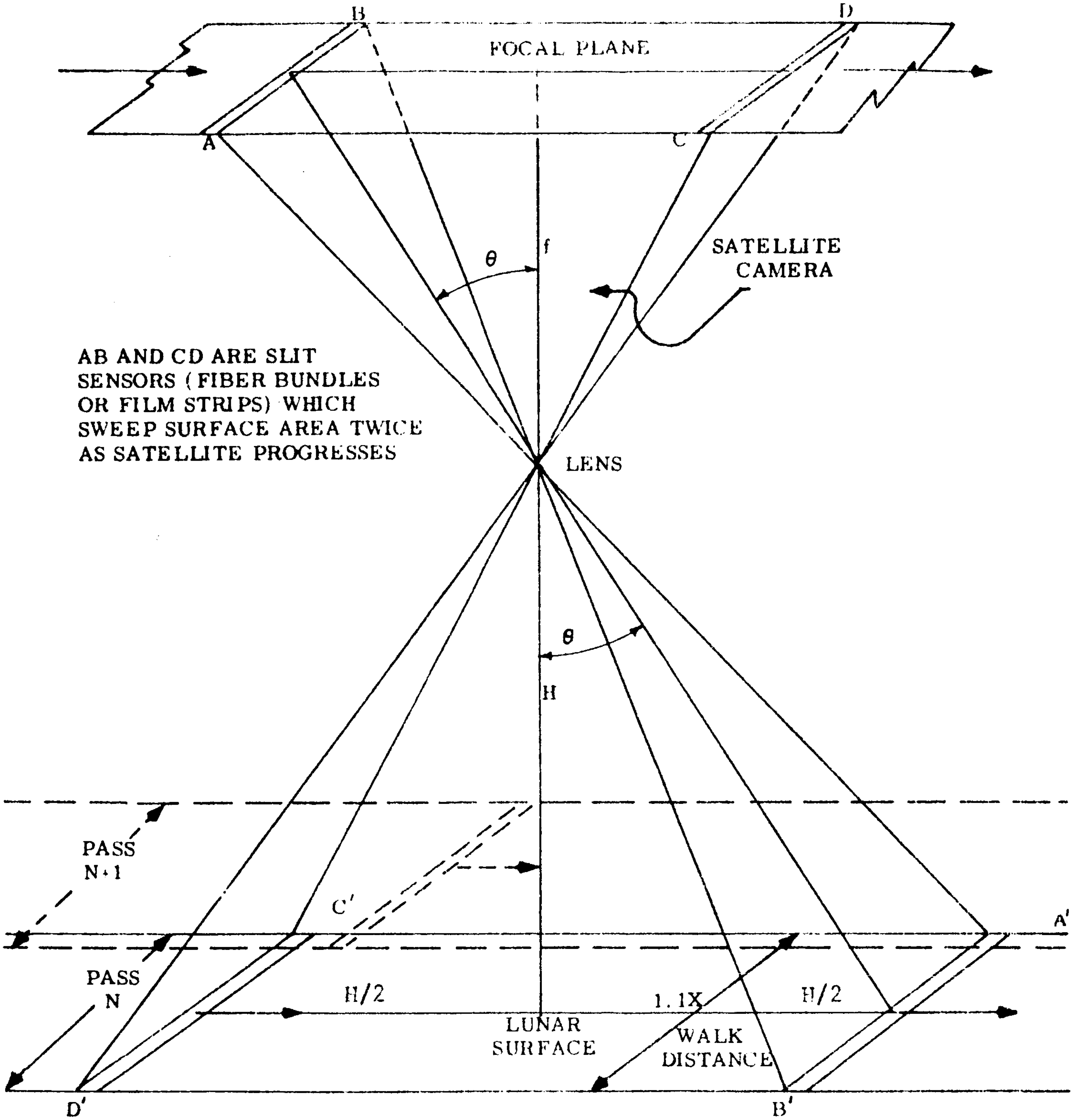
Temperature Control

The problem of temperature control within a camera has been met on many occasions. Many current reconnaissance cameras have heating elements built into the camera body and fine heater wire elements near or within the lens elements. These elements hold the camera temperatures to 45°F $\pm$15°F. This range is adequate for short focal length cartographic system. However in the long focal length systems, temperature gradients cause severe troubles. For a large reflector system the temperature should be controlled to $\pm$3°F since reflectors are extremely sensitive to temperature gradients.

Photographic systems can be designed to operate at almost any reasonable temperature, being cognizant of lens cement problems. Therefore the important temperature control problem is the variation from design temperatures and gradients within the structure.

3.2.1 Cartographic Cameras General

The fore/aft stereo configuration for the cartographic camera (Figure 3.1) appears to be the best approach for the lunar mapping program. This choice is predicated upon the unit having a constant depth sensitivity (as contrasted with the sidelap stereo system which has a depth sensitivity that is a function of cosine of latitude) and upon economy of required video storage for periods when line-of-sight read-out is not possible nor desired. Due to the nature of the highly unique fiber optics/vidicon image sensor which scans the lunar surface one can contemplate camera configurations where a single camera contains several of these line sensor pairs. These are in addition to the two line sensors that transmit image data to the vidicon tube. One can place secondary or back up fiber line pairs to a second or third vidicon tube.



FORE AFT STEREO
CONFIGURATION

FIGURE 3-1

Redundancy of this type greatly enhances system reliability with very little weight and power consumption penalty. This situation differs significantly from frame cameras where the whole useful focal surface is filled with an area of film which is exposed and then transported out of the focal plane.

One highly unique advantage of the optical fiber sensor is the rigidity with which it fixes the internal camera geometry. After installation of the line element sensors the camera may be completely calibrated to account for all nonlinearities. In addition certain fibers may be blocked out (or broken) to generate calibration grid lines during operation which will allow correction of electronically induced nonlinearities. This advantage allows the use of reconnaissance camera lenses instead of conventional cartographic lenses for the lunar orbiter program. A reconnaissance lens differs from a cartographic lens basically as follows:

A) The cartographic lens has slightly better linearity characteristics over the whole <u>area</u> of the focal plane to be used for imaging surface detail upon film.

B) The cartographic lens weighs approximately an order of magnitude more than an equivalent (same focal length and f number) reconnaissance lens because of the required additional glass elements to create the extra linearity quality.

In the initial analysis of the cartographic problem a single lens camera was suggested that incorporated two fiber line sensors to obtain the stereoscopic coverage. Detailed examination however suggests that a multi-lens camera has advantages. Since the weight problem is alleviated by the use of calibrated reconnaissance lenses, both a single and multiple lens cartographic camera have been designed. The focal length of the lenses used in the illustrative examples are, as mentioned, 12 inches. This document includes an anlaysis of the different modes of system operation using 10 and 30 meter cartographic camera resolution. This camera resolution change would be achieved either by using a reconnaissance lens of different focal length or by retaining the 12 inch lens and increasing the diameter of the optical fibers in the sensor and having a commensurate change in vidicon read characteristics. The camera design illustrated for the

12-inch/10 meter resolution cartographic camera remains completely sound for either of the above-mentioned changes.

3.2.2 High Acuity Cameras General

The three problems that create the greatest difficulty in the design and fabrication of long focal length high acuity cameras for reconnaissance purposes are the current trend of requirements for large angular fields of view, resolution in excess of 125 photographic lines/mm and high optical aperture speed. After a complete parametric study of the requirements of the lunar orbiter high acuity camera one finds very fortuitously that requirements in each of these areas are not as severe as those currently being expressed for terrestrial work.

The parametric study suggests that the width of the swath photographed by the high acuity camera be approximately 0.1 that of the cartographic camera. Therefore the widest contemplated swath width would be for the low altitude vehicles and would require less than 2.5° angular field of view for a vehicle at 100 KM altitude. At higher altitudes this angular value would decrease somewhat, depending primarily upon roll stability of the vehicle and/or camera directing equipment accuracy. As for large aperture problems, the expected lighting and image contrast levels combined with vidicon sensitivity suggest that adequate operation can be achieved using cameras having characteristics of T/10 to T/16.

As described within the parametric study, the system resolution is a function of optical fiber diameters and vidicon electron beam dimensions. Using the values discussed in the study (21μ fibers) illustrates that there is no necessity to try to achieve systems with final resolutions in excess of 30 photographic lines/mm. Detailed examination of these requirements by several lens designers indicate a simple Cassigrainian telescope or a rather lightweight refractor (a modified Petzval or Cooke triplet) will meet the system objectives. One major advantage of the optical fiber sensor is the ability to contour the entrance plane of the sensor to account for curvature of focal plane that results with the two imaging systems mentioned. Since the angular field of view is less than 2.5° the off-axis problems incumbent upon both systems is also alleviated.

To illustrate the magnitude of weight savings effected by the use of the simpler systems consider two current cameras designed to meet objectives of large aperture, high resolution and field of view of approximately 10°. Both systems have a focal length of only 72 inches which is 60 percent of that required by a 100 KM altitude lunar orbiter.

<u>Catadioptric System of Maksutov Type</u>*

Focal ratio	f/3
Weight glass above	460 pounds
Camera weight total	920 pounds

<u>Refractor System</u>

Focal ratio	f/4
Weight glass above	520 pounds
Camera weight total	1200 pounds

Neither of these weights include a training or pointing mirror. This could easily add 150 pounds of glass to the above plus support and drive mechanism. The major weight of glass is contributed by large thick correction plates to

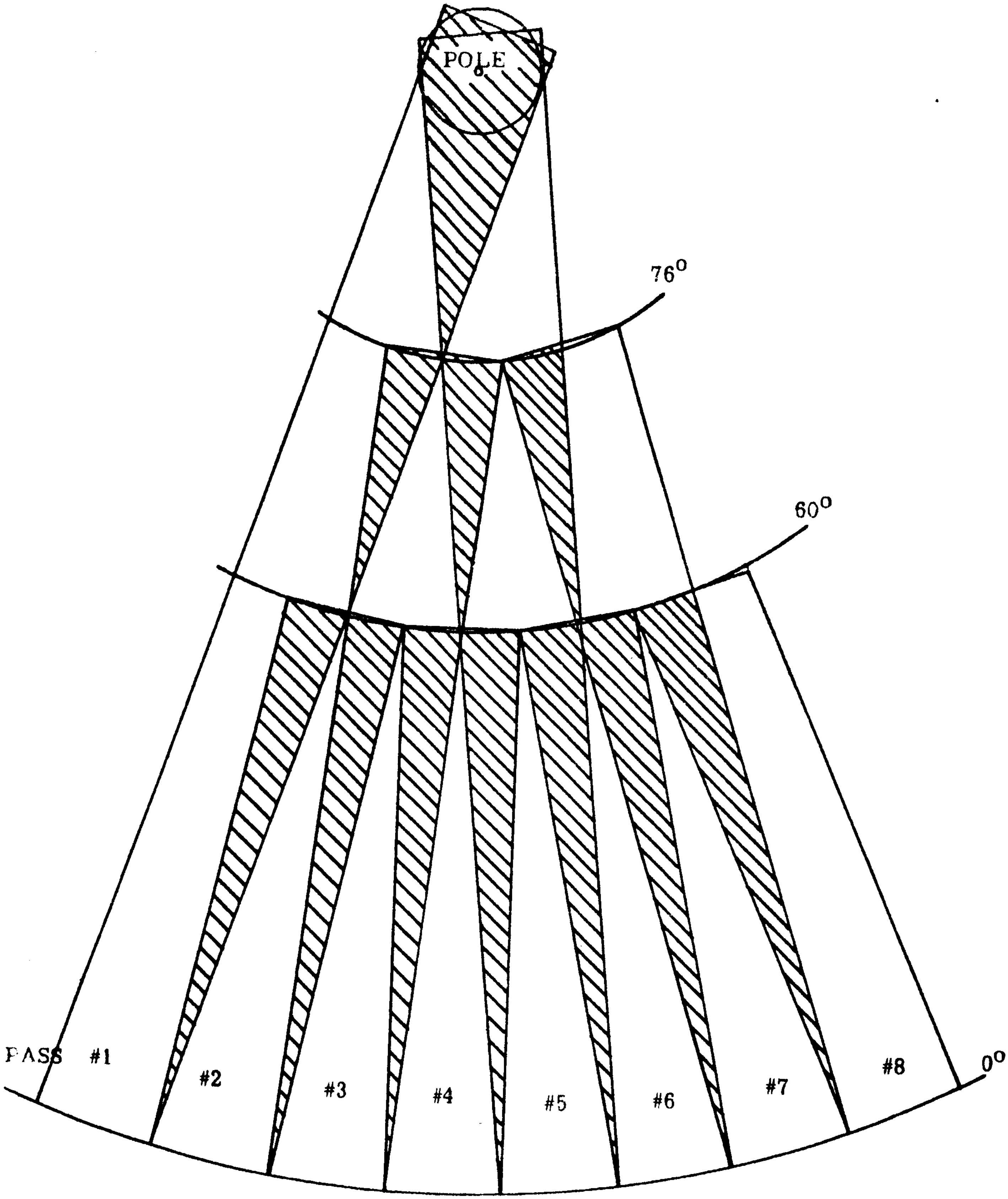
*Modified Schmidt system.

give high resolution over the 10° field plus field flatteners so that photographic film might be used. Compatible cameras of 120-inch focal length would be much heavier. Since it is desirable not to exceed 200 to 300 pounds total weight for the lunar orbiter high acuity camera the use of simple optical systems requiring less glass becomes mandatory. Detailed discussion of recommended VOIS high acuity cameras is found in section 5.3.2.1.

3.3 REDUNDANCY

Assuming no regression of orbit, the advance at the Lunar Equator per orbit is equal to 32.8 KM for an altitude of 100 KM. A 5% overlap condition yields a swath width of 34.45 KM and a total area of swath of 187×10^3 square kilometers. Since the satellite makes 332.6 orbits in one sidereal period, the VOIS system will scan a total of 62.1×10^6 KM^2. Since the surface area of the moon is equal to 38.0×10^6 KM^2 the resultant lateral redundancy is 63.5%. In view of the fact that a limited time is available for transmission, at the stipulated information rate, (10^6 stereo elements per second) a system for programming the mapping function for reduced redundancy may be advantageous.

A program for reducing the redundancy is one in which the VOIS is inactivated for the high latitude portions of specific orbits. Figure 3.2 depicts a four orbit, repetitive system in which pole-to-pole scanning will occur only during the first orbit. The second and fourth orbits require scanning between latitudes of plus and minus 60° and over the third orbital period of the program the instrument will operate between the 76° latitudes. At the end of the fourth orbit the cycle repeats.



COVERAGE REDUNDANCY DUE TO FIXED SWATH WIDTH OF SENSOR SHOWN AS HATCHED AREA

FIGURE 3.2

The result is a scanned area of <u>49.9×10^6 KM^2</u> representing a lateral redundancy of only <u>30.5%</u>.

As was previously explained, for stereoscopic mapping at least 100% redundancy is required. However, the method for obtaining this double coverage requires a forward and rear looking system, and the <u>lateral</u> redundancy which occurs at the high latitudes is not usable.

The total time available for transmission of mapping information to the earth from the vehicle, is dependent upon the existence of the line of sight. This LOS exists approximately 75% of sidereal period, however, 10 meter cartographic mapping occurs for only 50% of the period. Therefore, 25% of the period is available for transmission of high resolution information. If a programmed mapping function is adopted, a portion of the transmission time formerly wasted on redundant low resolution information can be utilized for additonal high resolution transmission. A system similar to that described above will conserve an additional 10% of the total time for high resolution data. This increases the high resolution transmission time from 25% to 35% of the sidereal period representing a 40% increase in transmission of high resolution information.

During specific portions of the sidereal month, real time, low resolution mapping consumes all but 10 minutes of the available transmission time in each orbit. Since high resolution mapping takes place at approximately 4 times the information rate that can be transmitted, only 2 1/2 minutes are available for high resolution mapping. Programming the mapping in the four-orbit repetitive system described previously permits use of those portions of the cycle during which 10-meter cartographic mapping equipment is inactivated. For example, the time available for high resolution transmission over a typical four-orbit period can be increased from 40 minutes to 74 minutes, and in an orbit, such as the second or fourth of the cycle, the time increases from 10 to 28 minutes.

4.0 PARAMETRIC STUDY

One of the prime objectives of the lunar orbiter study program is to investigate the many parameters which will have an impact upon the design of the final operational equipment. The attempt of this parametric study is to determine the trade-offs which will exist between the lunar orbiter program objectives and various operational concepts or system modes. The ultimate fixing of design parameters upon a discrete set of conditions defining a unique system, must be attempted only after a detailed analysis has been made of these parametric studies.

It is obvious from the beginning that all users participating in the operational lunar orbiter program cannot be satisfied to the fullest extent. Compromises must be made in nearly all areas. Available electrical power, transmission bandwidth, orbital altitude, to mention only a few parameters, all have far reaching impact upon the extent to which a particular system objective can be achieved, or a design concept implemented.

The purpose of this study is the examination of the problems incumbent upon the visual observation instrument sub-system. As will be seen, this analysis cannot be made in a vacuum. The study which should be confined neatly to the VOIS problem is continuously forced to draw data from beyond the boundaries of the specified sub-system. From the beginning, it has been necessary to accept compromises which are dictated by operational problems, other sub-system capabilities, and the lunar environment.

In order to illustrate the order of dependence of variables pertinent to this study program a parameter interaction flow diagram has been prepared (see Figure 4.1). By referring to this diagram one can take a particular parameter and observe the items which are affected by change of this variable. Similarly, one can determine the other variables which have an impact upon the chosen parameter. As an example, one can enter the diagram with the vehicle operational altitude and immediately observe that swath overlap factor, walk distance (distance between equatorial crossings), tracking occlusion periods, vehicle ground velocity, periods of solar energy availability, and camera focal lengths all are directly affected by initial attitude and altitude variations. Similarly, one can observe that camera focal length is a direct function of optical fiber size, Kell factor, vehicle altitude and desired ground resolution.

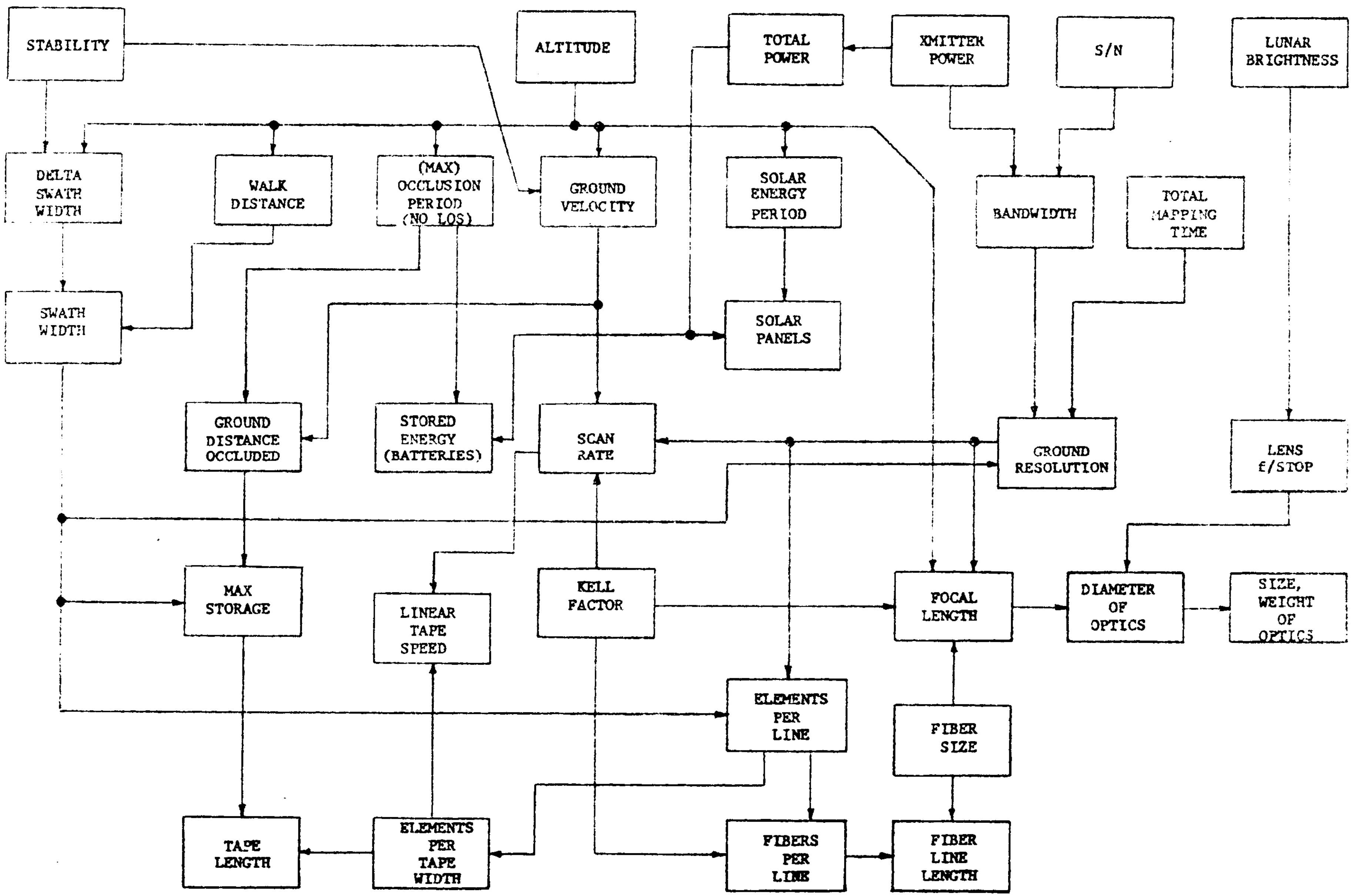


FIGURE 4.1

PARAMETRIC INTERRELATIONSHIPS

The range of reasonable variation conceivable for any one of the parameters is quite large. Attempts to vary all parameters through their reasonable range and observe the primary, secondary and higher order effects upon other parameters, which themselves are not constants, are neither possible nor desirable.

Based upon our past experience in highly pertinent and related areas, we have chosen to vary the parameters which we feel have the greatest significance to this initial study phase. As a result of the data analyzed in this parametric study, we are able to describe an exemplary system which obtains maximum return for the lunar orbiter program objectives.

It is probable that events will arise during subsequent program phases of breadboarding and implementation which will suggest a variation from the system currently envisioned. These events will be readily met when encountered. There is no feeling that the current exemplary system is rigid or sacred.

4.1 ALTITUDE AND ATTITUDE CONTROL

The mapping satellite will be designed to orbit the moon in straight and level flight. It will, however, encounter various forces tending to cause its deviation from this ideal path and, as a result, corrections must be made on a more or less regular basis. It is the purpose of this subsection to determine the effects of these deviations so that appropriate excursion values may be selected for the exemplary systems described in section 5.0.

A set of four curves (Figures 4.2 through 4.5) is given to illustrate the dependence of cartographic swath width upon various degrees of attitude stability and altitude control. The initial criteria are as follows:

The nature of the cartographic bridging and tieing that will be done to extend cartographic control from pass to pass to result in a final map requires that a minimum of 5% overlap be maintained between adjacent passes. As can be readily

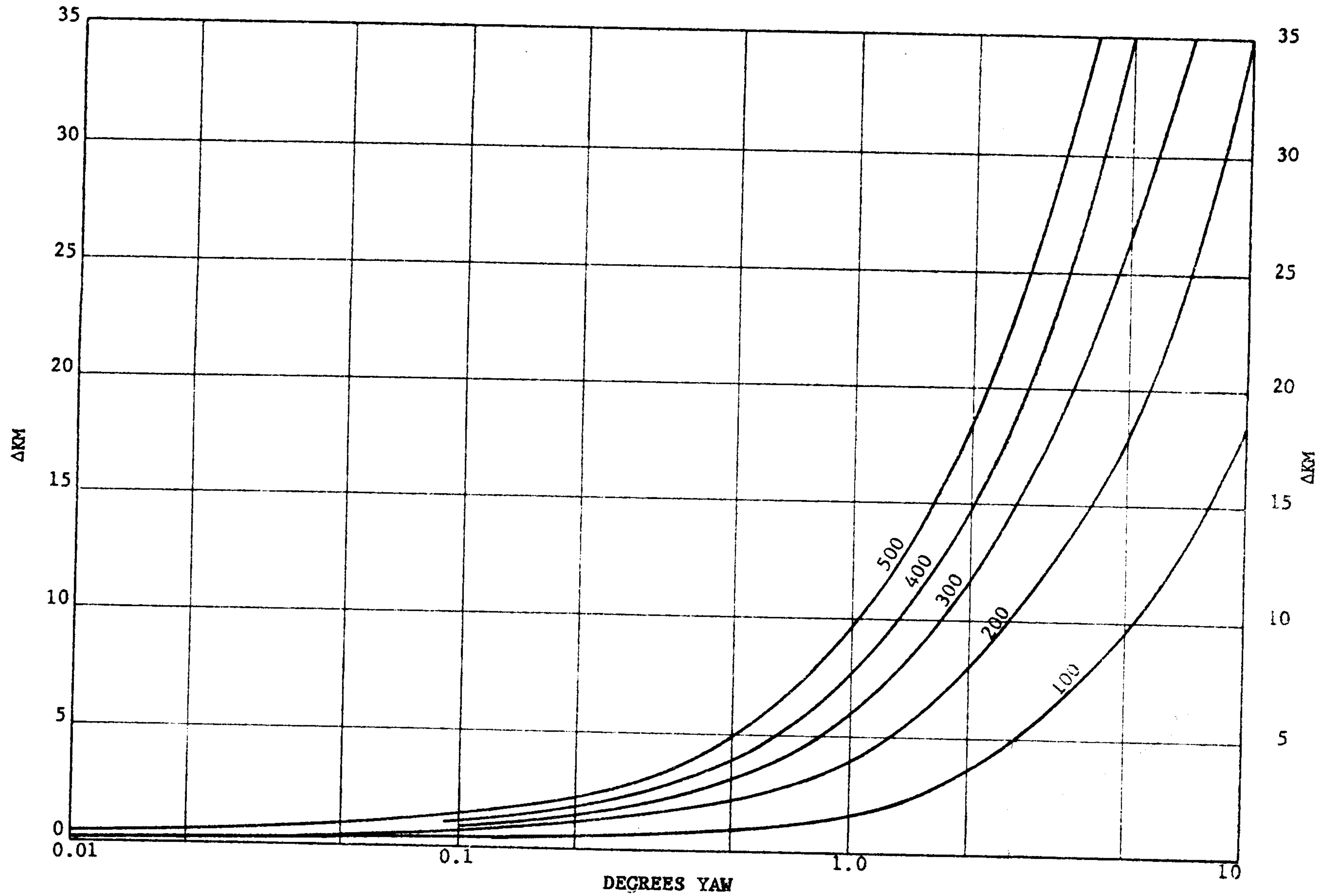


FIGURE 4.2

Δ SWATH WIDTH VS ANGLE OF

YAW FOR VARIOUS ALTITUDES

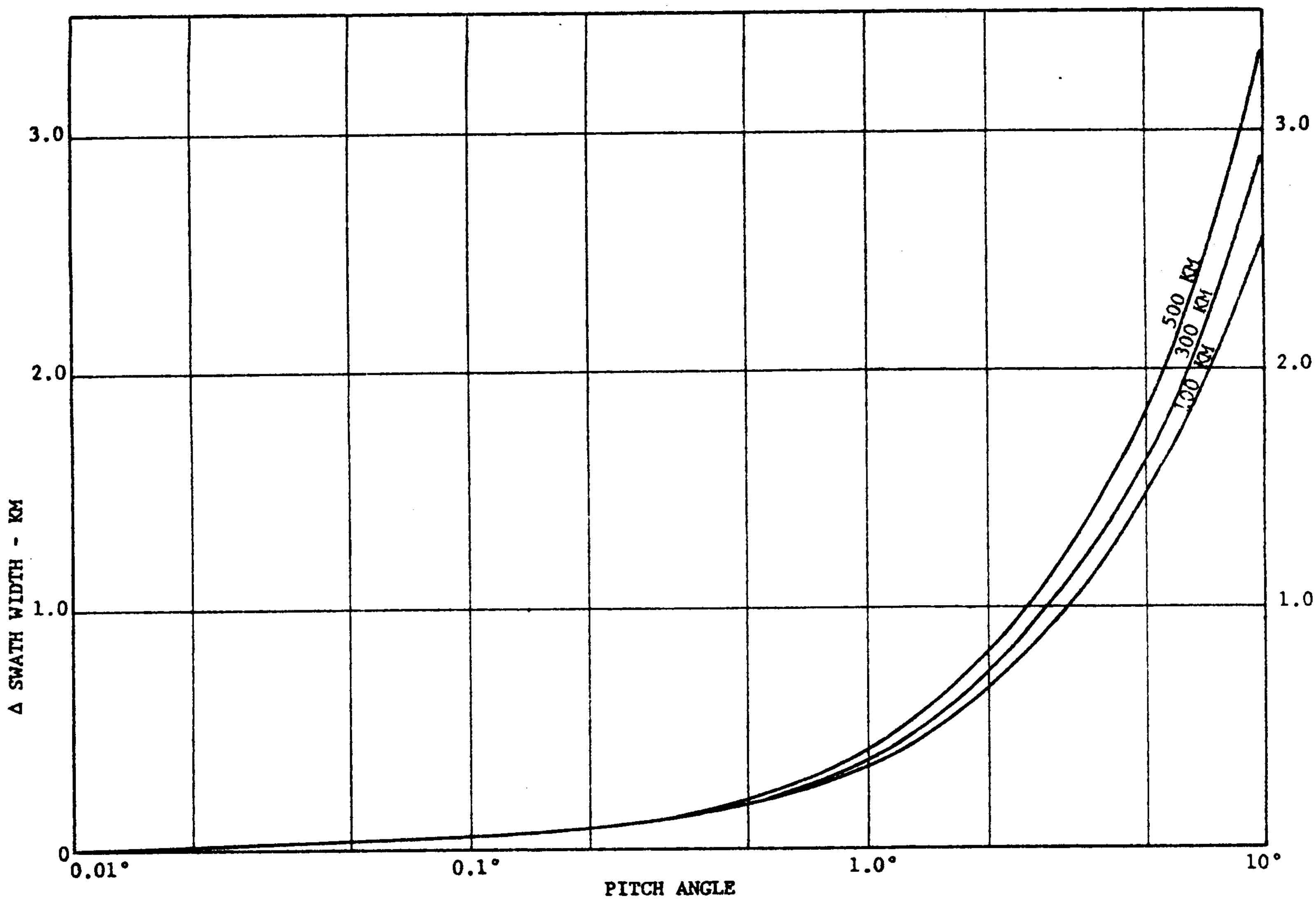


FIGURE 4.3

Δ SWATH WIDTH VS ANGLE OF

PITCH FOR VARIOUS ALTITUDES

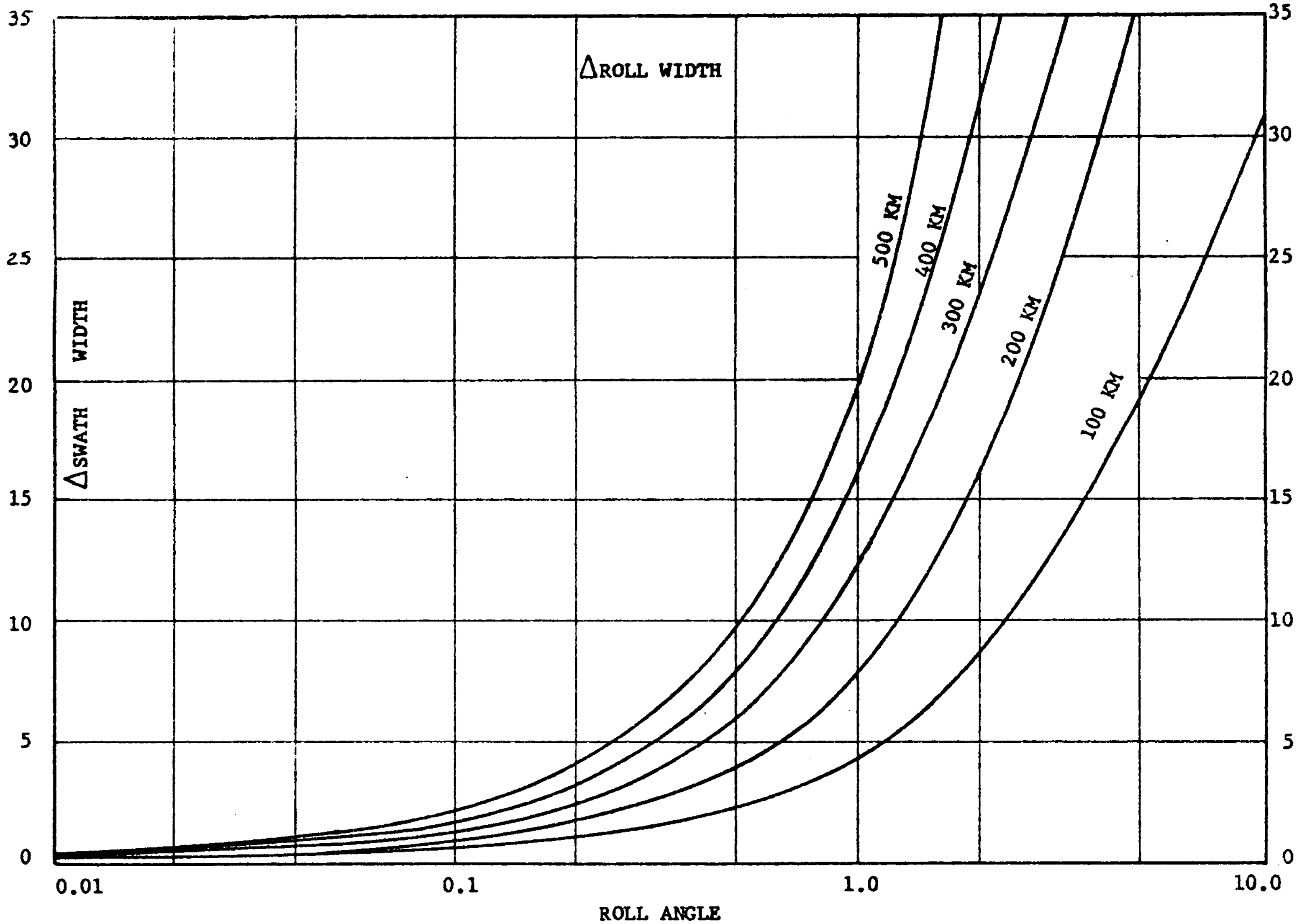


FIGURE 4.4

Δ SWATH WIDTH VS ANGLE OF

ROLL FOR VARIOUS ALTITUDES

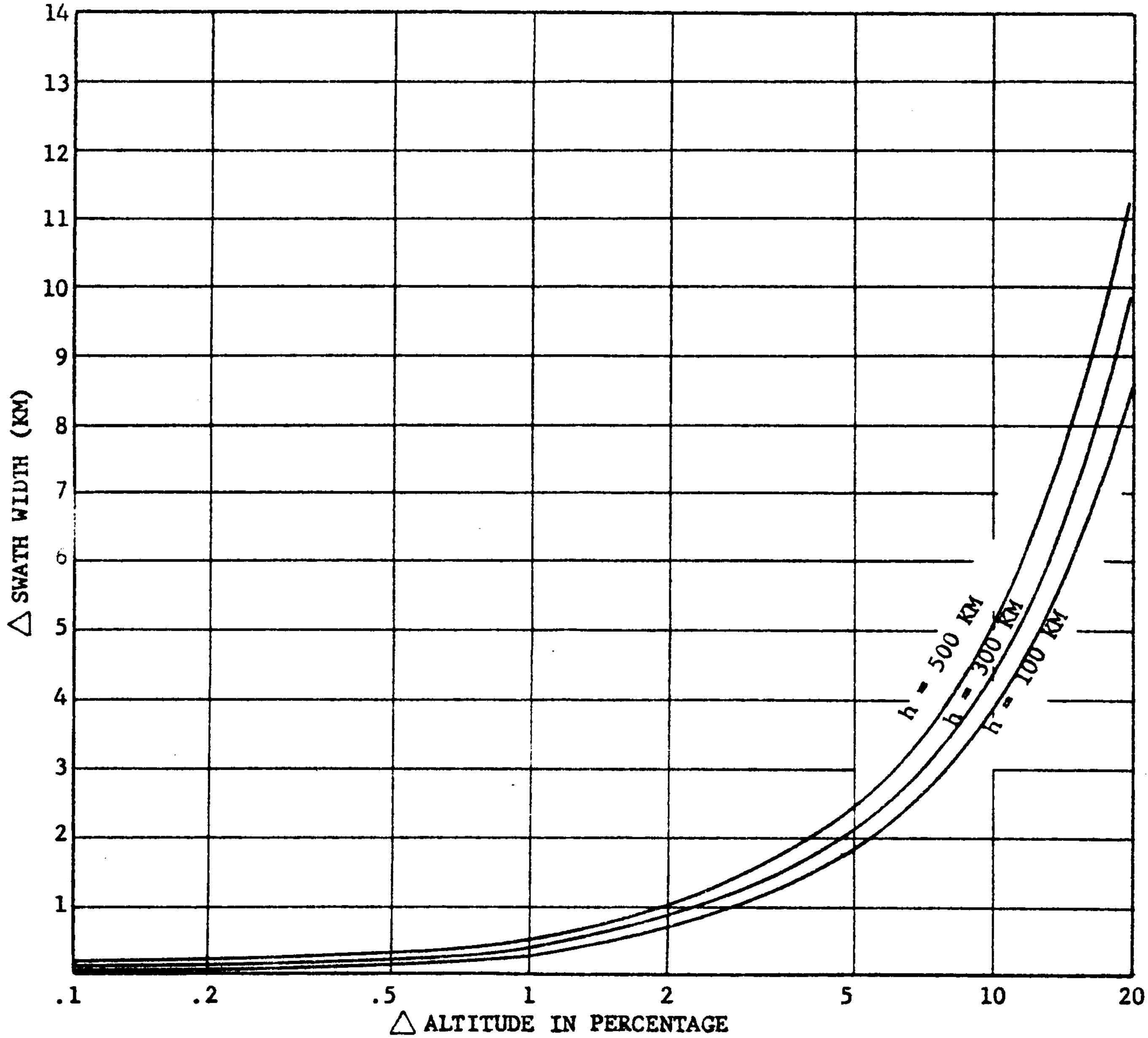


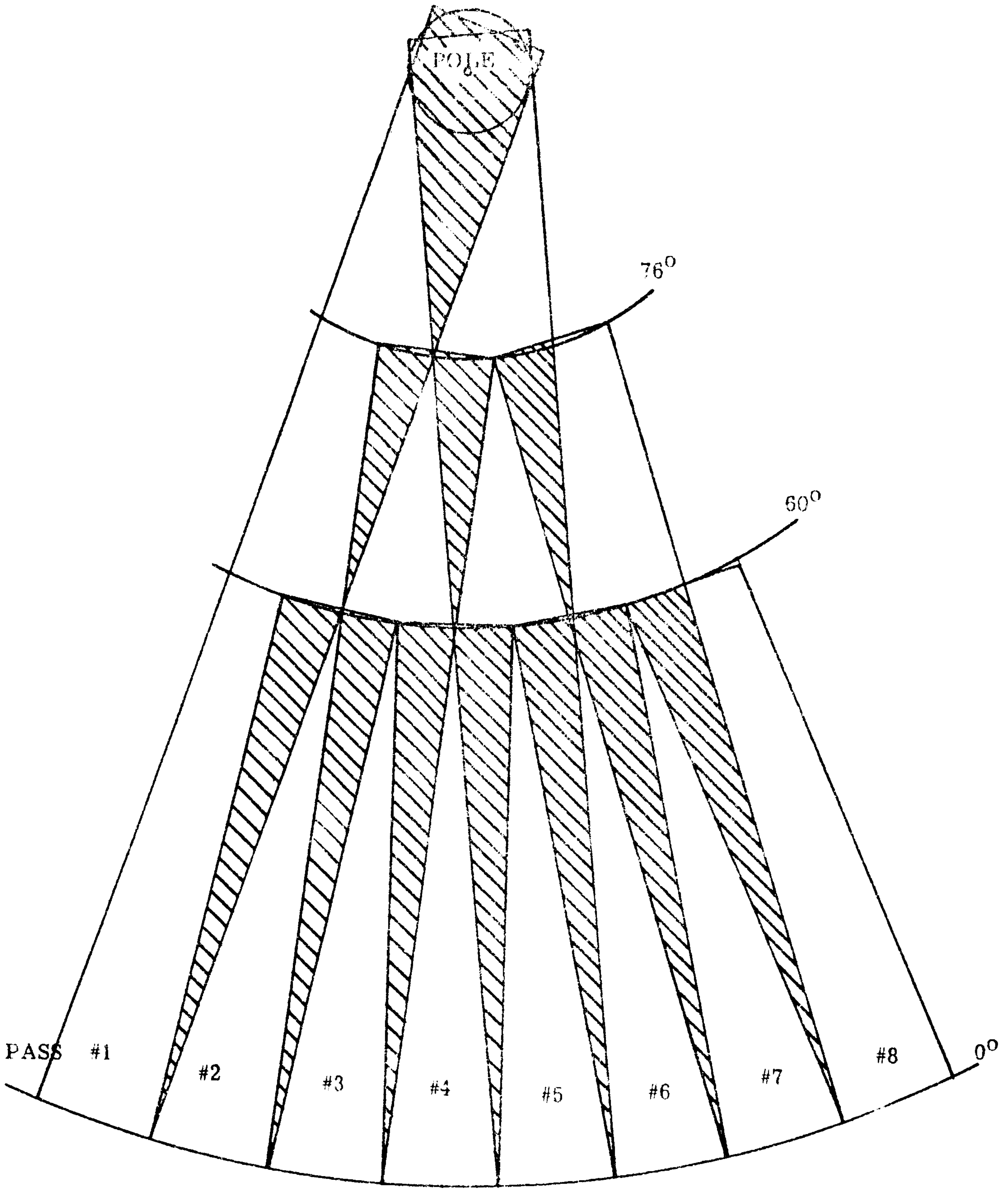
FIGURE 4.5

SWATH WIDTH VS. PERCENTAGE CHANGE IN VEHICLE ALTITUDE FOR VARIOUS ALTITUDES seen in Figure 4.6 which illustrates the pole to pole/$\pm 60°$/ $\pm 76°$ mapping program, these minimum overlaps will occur at the lunar equator, $\pm 60°$ and $\pm 76°$ latitudes. Successive orbits are displaced along the lunar equator by a distance (walk distance or W.D.) that is a function of vehicle altitude*. Therefore for any given altitude the minimum acceptable swath width for cartographic coverage is taken as 1.05 W.D. (see Figure 4.7). Change of altitude results in a change of ground swath swept out by the cartographic camera (refer to Figure 4.8). Similarly changes in attitude result in more or less ground coverage by one or both of the cartographic cameras. The following is a brief tabulation of the effects of attitude and altitude changes upon the cartographic swath:

<u>Altitude Variations</u>

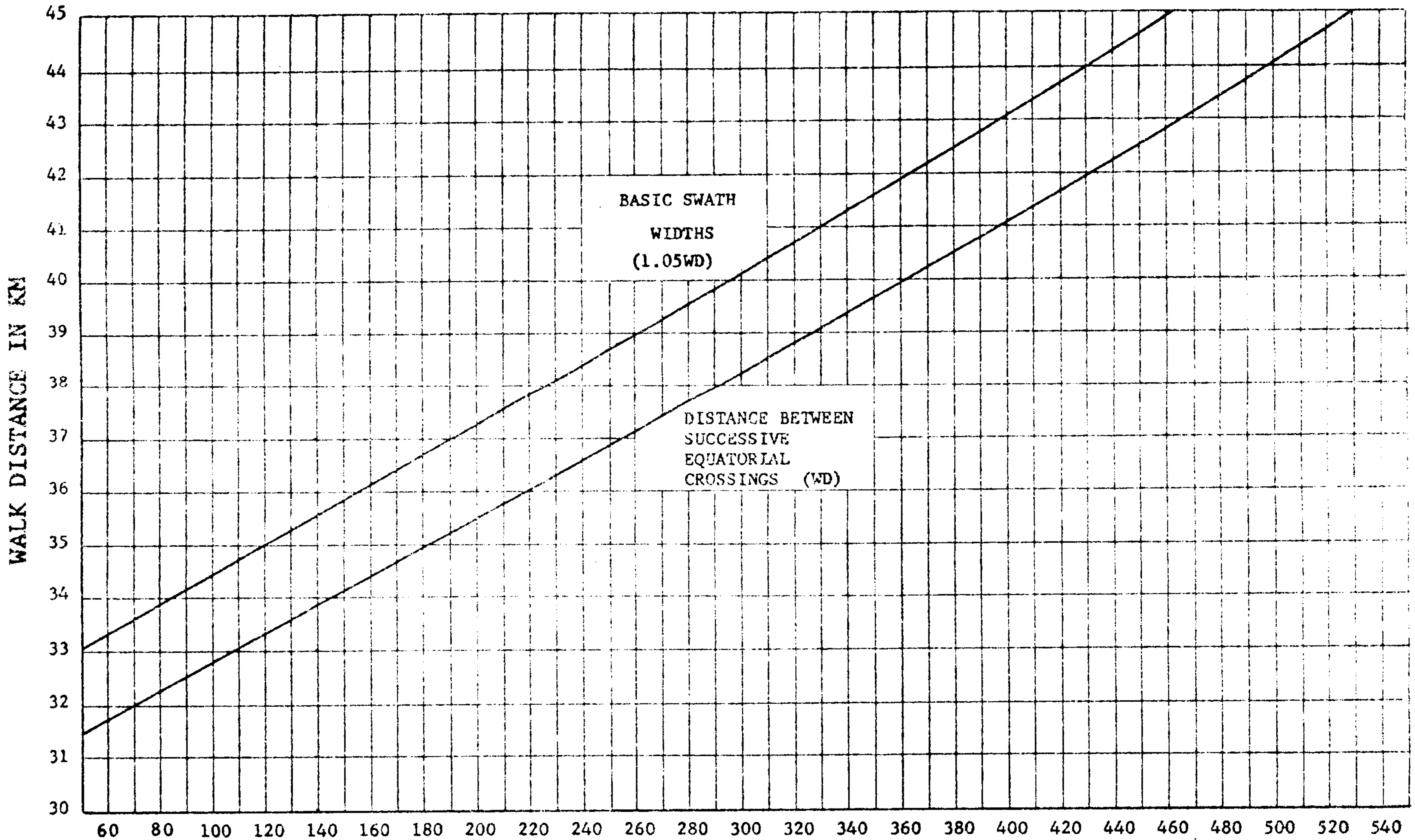
$$\Delta wh = \frac{w \Delta h}{1 - \Delta h}$$

*W.D. = $4.1549 \times 10^{-4} r^{3/2}$, where W.D. = equatorial walk distance, and r = distance from lunar center to satellite, or r = 1740 + H KM. All dimensions in kilometers.



COVERAGE REDUNDANCY DUE TO FIXED SWATH WIDTH OF SENSOR SHOWN AS HATCHED AREA

FIGURE 4.6



$$W = \frac{(8.99 \times 10^{-2})(10,910)}{2.36 \times 10^6}\ r^{3/2} = 4.1549 \times 10^{-4} r^{3/2}$$

$r = (R+h) - R = 1740$

FIGURE 4.7

WALK DISTANCE VS. VEHICLE ALTITUDE

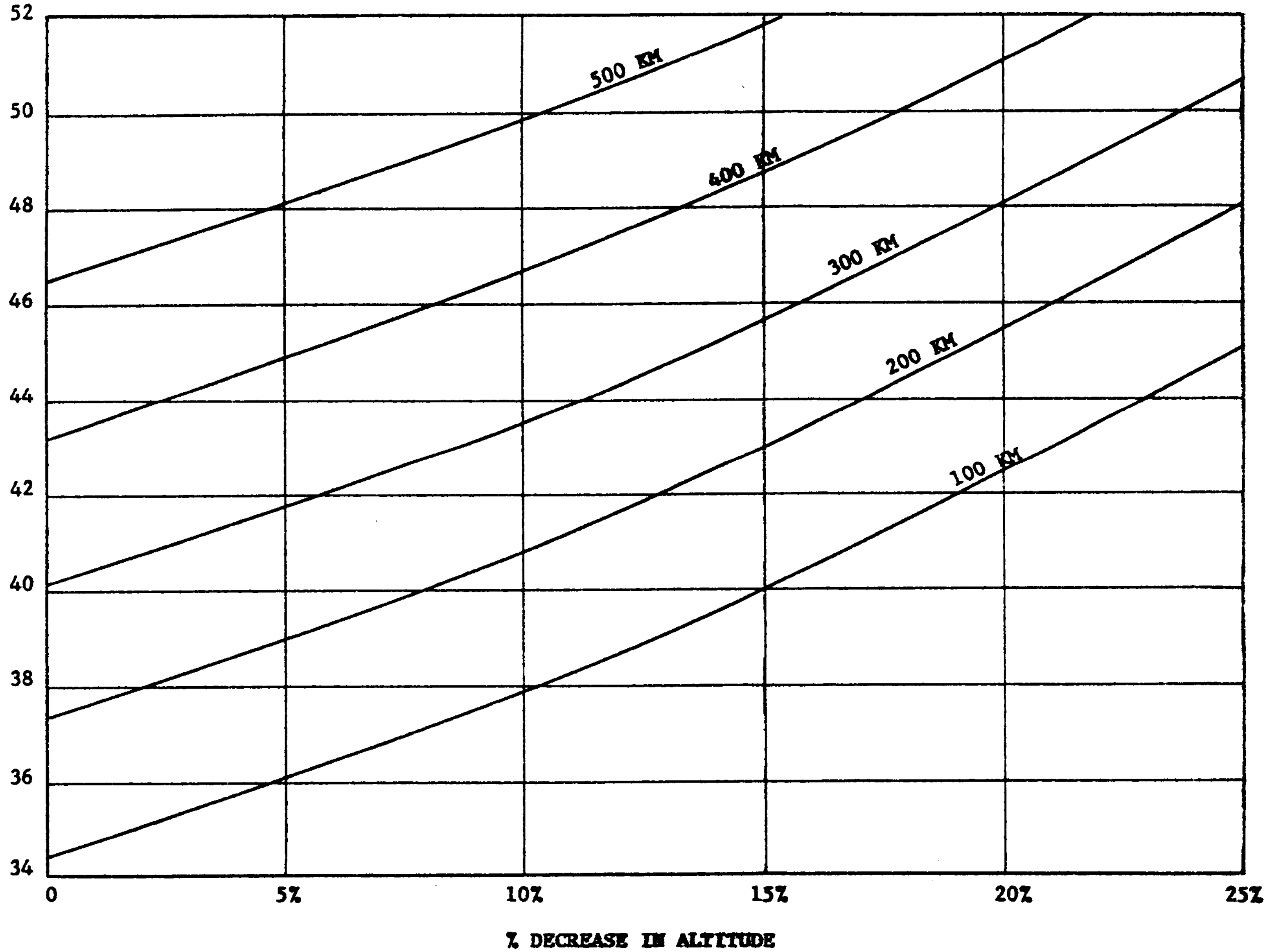


FIGURE 4.8

SWATH WIDTH REQUIRED VS ALTITUDE VARIATION

Δwh is the increase in swath width in KM necessitated by the altitude excursion Δh expressed as a fraction of the altitude h.

w is the basic swath width and is 5 percent greater than the walk distance.

A) Increase of altitude results in coverage of a wider swath.

B) Decrease of altitude results in coverage of a narrower swath.

<u>Pitch Variation</u>

$$\Delta wp = w(1 - \frac{\cos 26.5°}{\cos(26.5° - \Delta p)}$$

Δwp is the increase in swath width necessitated by the pitch excursion Δp.

26.5° represents the angle of fore or aft "look" required by a unity B/H stereo system.

The camera is rigid, hence the geometry of the two angular coverage cones is fixed. Pitch results in the narrowing of one angular coverage swath and the widening of the other swath.

Roll Variation

$$\Delta wr = 2h \tan(\tan^{-1} \frac{w}{2h} + \Delta r) - w$$

Δwr is the increase in swath width necessitated by the roll excursion Δr.

Again, due to camera rigidity, roll results in the loss of coverage on the same side by the fore and aft looking cameras plus a gain of coverage by both coverage cones on the opposite side of the swath.

Yaw Variation

$$\Delta wy = \sin(\tan^{-1} \frac{w}{h} + \Delta y) \sqrt{h^2 + w^2} - w$$

Δwy is the increase in swath width necessitated by the yaw excursion Δy.

Due to geometric rigidity, yaw results in a gain of coverage on one side by one camera coverage cone and loss of coverage on the same side by the other camera coverage cone.

In the analysis of effects of altitude and attitude variation the following criteria has been established.

After any change the minimum swath width having <u>common</u> coverage by both cartographic cameras must be 1.05 W.D. Calculations were then made to determine the required initial swath width such that a given change does not result in less than the specified 5 percent minimum overlap. The first four curves show the required swath widths as a function of attitude or altitude variation for various vehicle altitudes. The second set of four curves shows the increment of swath width in kilometers that must be added to a given minimum camera coverage to account for a specific altitude or attitude variation. This second set of curves is prepared for ease in combined error analysis.

<u>Specific Example</u>:

Many references are made to a cartographic satellite operating at a nominal altitude of 100 KM. At 100 KM the walk distance is 32.8 KM hence the minimum acceptable cartographic swath width must be 1.05 x 32.8 = 34.45 KM. Consider a stability control system that can hold the following parameters:

Yaw	$\pm 2°$
Pitch and Roll	$\pm 1°$ each
Altitude	$\pm 5\%$

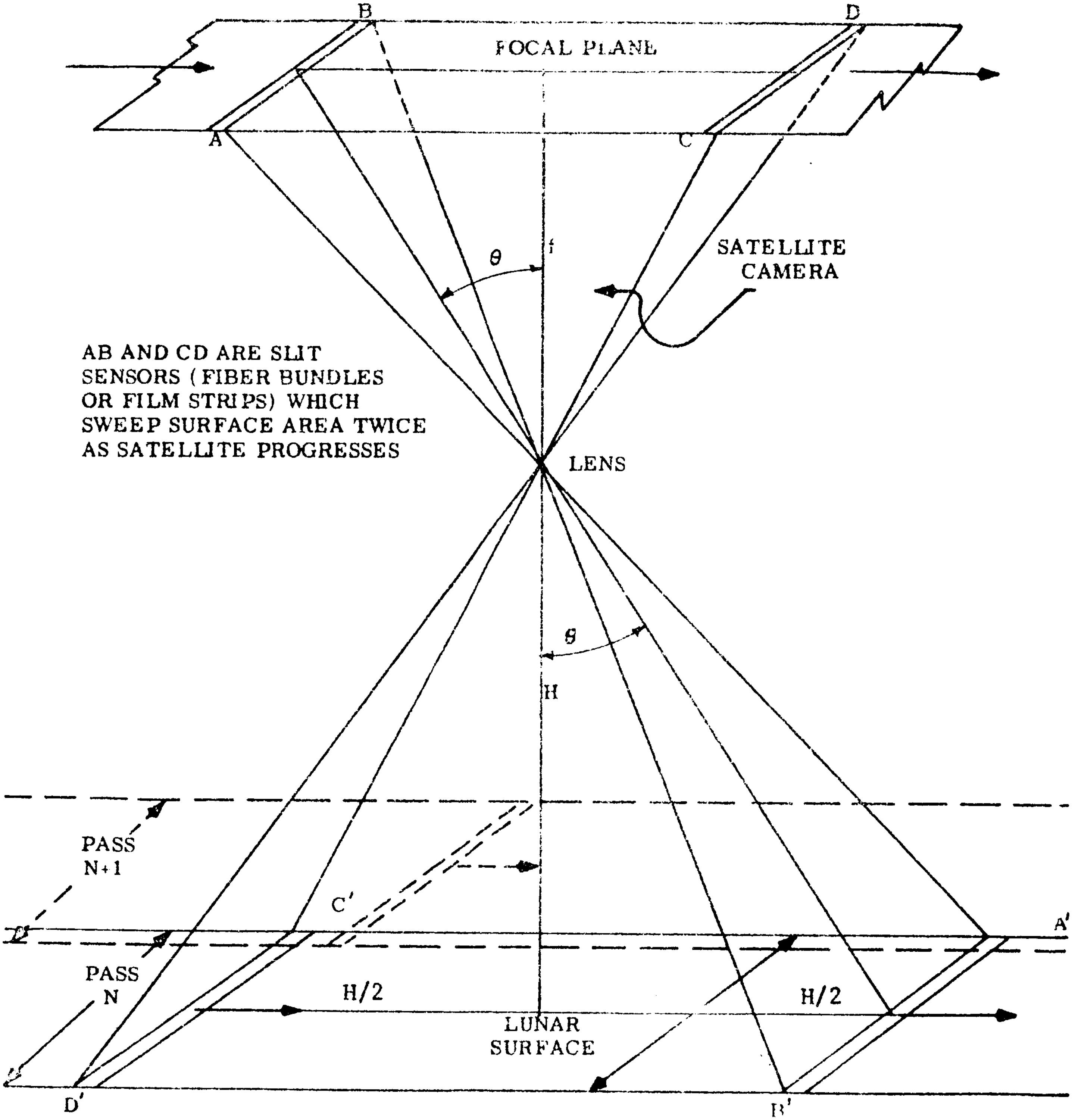
From the second set of curves or from the delta equations the swath width increments required to ensure adequate coverage with these variations would be

Yaw	3.47 KM
Pitch	0.29 KM
Roll	3.64 KM
Altitude	1.82 KM

The RSS (root, sum, square) of these increments is 5.35. Therefore the required swath width would be 34.45 + 5.35 = 39.80 KM. It is from this analysis that an approximate swath width coverage of 40 KM arises for the 100 KM system.

This value will be used in other sections of the document for ease of illustrative calculations.

It is interesting to note the relative insensitivity of the camera to pitch variations as compared to roll. Pitch and roll will probably be sensed and controlled by horizon sensors which respond to the vector sum of pitch and roll. It is therefore far more important to correct the roll component of the combined pitch/roll tilt. Mental rotations applied to the cartographic camera schematic drawing (Figure 4.9) will illustrate this effect fairly well.



FORE-AFT STEREO
CONFIGURATION

FIGURE 4.9

In practice the several deviations will occur simultaneously and it is pertinent to estimate the approximate combined effects. It is obviously highly improbable that all of the deviations will be maximum at any one time so that a design providing protection against the sum of the excursions is clearly not justified. Experience and logic indicates the use of the square root of the sum of the square of the deviations as a reasonable estimate and the curves of Figure 4.10 reflect the effects of RSS combining.

The effect on swath width of four degrees of stabilization are shown in the figure together with the width necessary with perfect control. The curve closest to the ideal represents fairly tight control and the uppermost curve relatively sloppy control.

In order to determine acceptable stabilization it is necessary to observe the effects of increased swath width on the system operation. Obviously this increased width represents undesirable redundancy. If we assume a bandwidth limitation of 1.0 MC, this redundancy must be reflected in reduced resolution. Figure 4.11 illustrates this effect and it will be noted that resolution, being a square root function, is not particularly sensitive to swath width. Accordingly

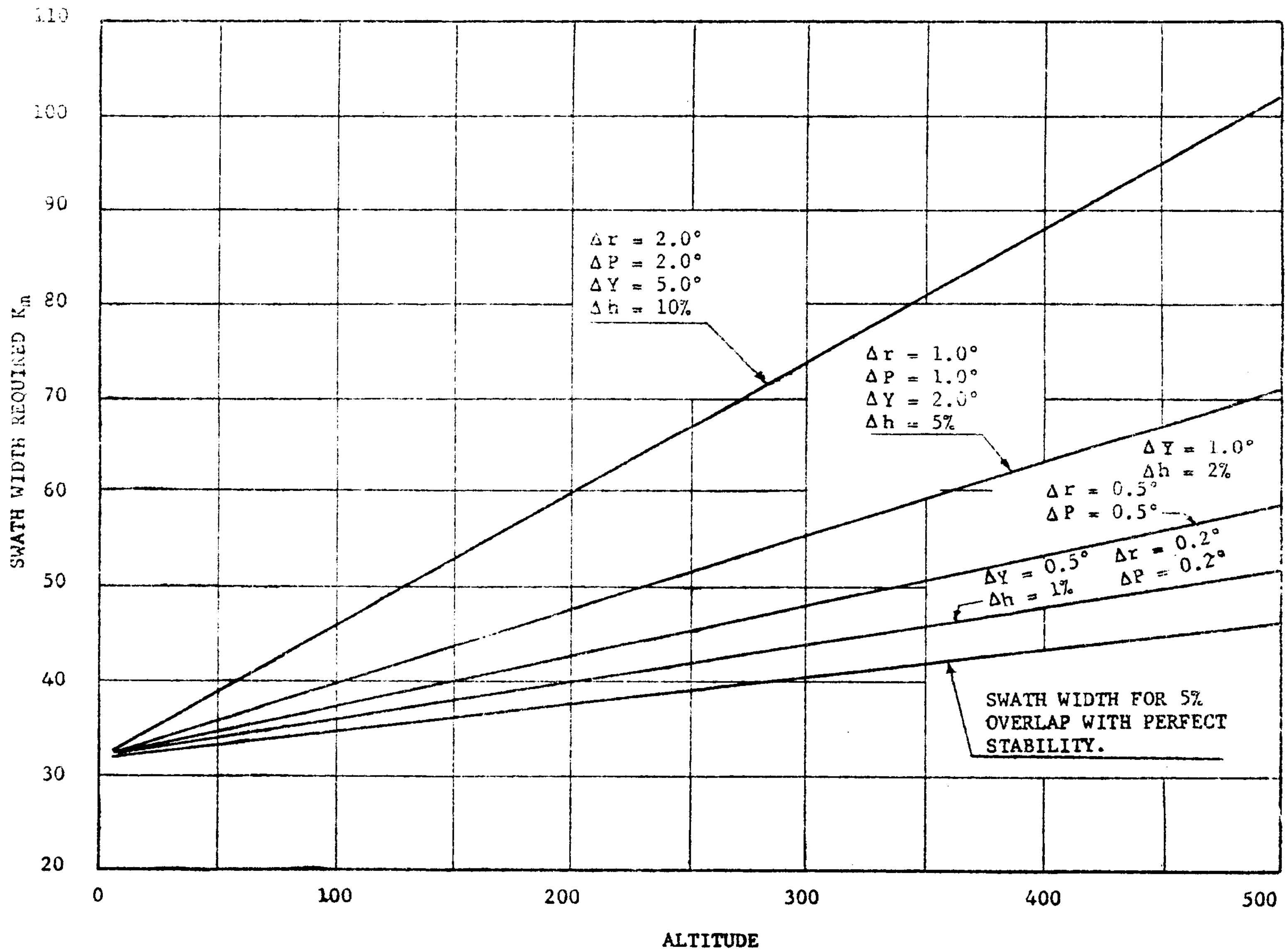


FIGURE 4.10

THE EFFECT OF SWATH WIDTH FOR 5° OF STABILIZATION

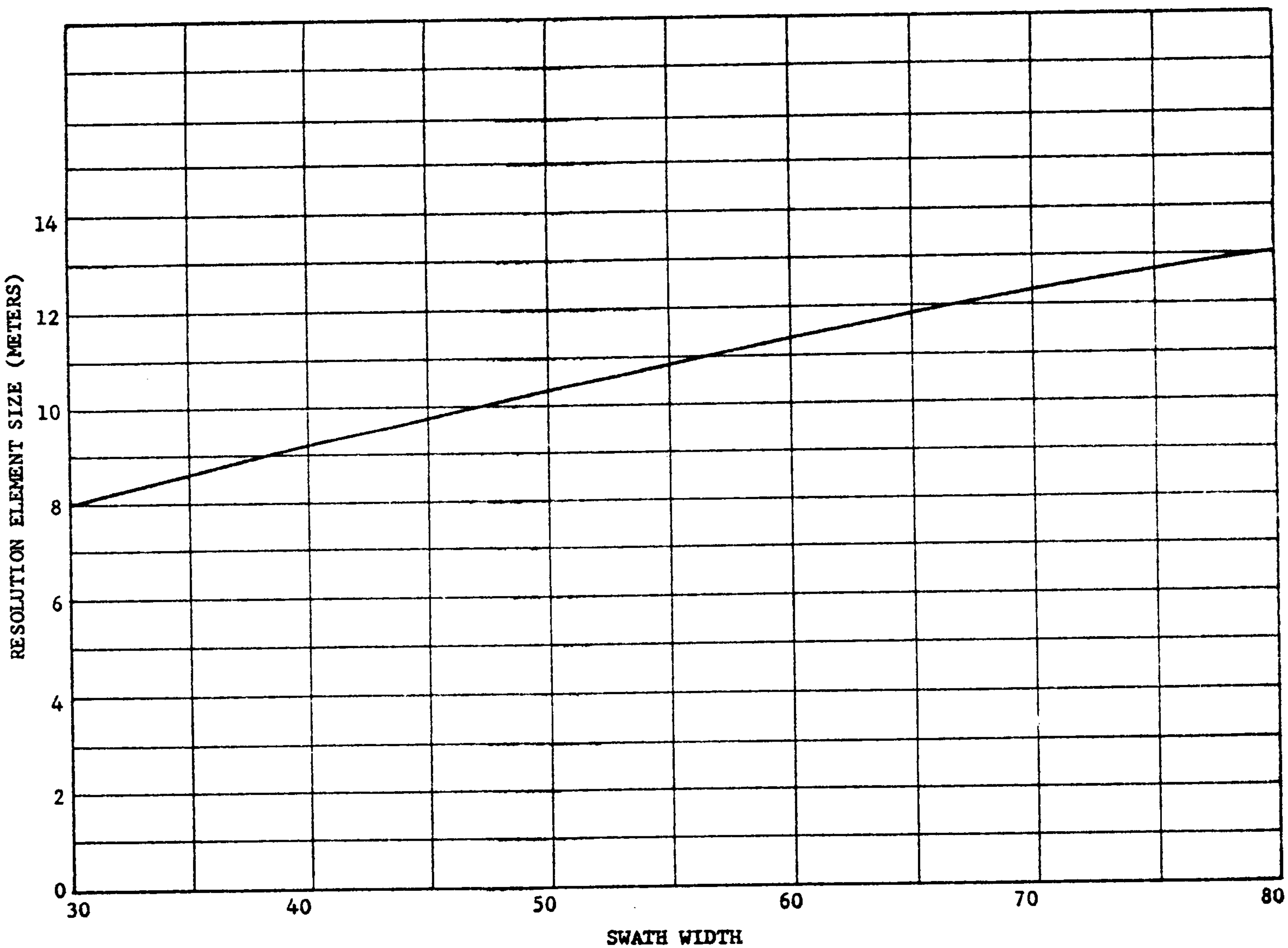


FIGURE 4.11

DECREASE OF RESOLUTION WITH INCREASE OF SWATH WIDTH OF FIXED ALTITUDE OF 100 KM very tight stabilization is not warranted so far as resolution is concerned. Another effect of instability is associated with the directing of the high resolution camera. Because of the bandwidth restriction it will be possible to map only a small percentage of the lunar surface in high resolution. Accordingly it is mandatory that those areas where high resolution is desired are, in fact, photographed.

In general it will be necessary to set the camera up in advance and have it activated and deactivated automatically. This is particularly relevant to photographing the far side of the moon but will probably be utilized for all high resolution shots. Clearly, without a tight stability control (or at least an accurate knowledge of attitude) the high resolution mapping function cannot be satisfactorily accomplished.

Figure 4.12 illustrates the linear distance by which the camera will miss the desired boresight as a function of uncompensated roll for several altitudes and degrees of stability. Figure 4.13 shows the percentage of the desired area which will actually be photographed under these conditions and it is apparent that, even with high stability, much desired information will be lost.

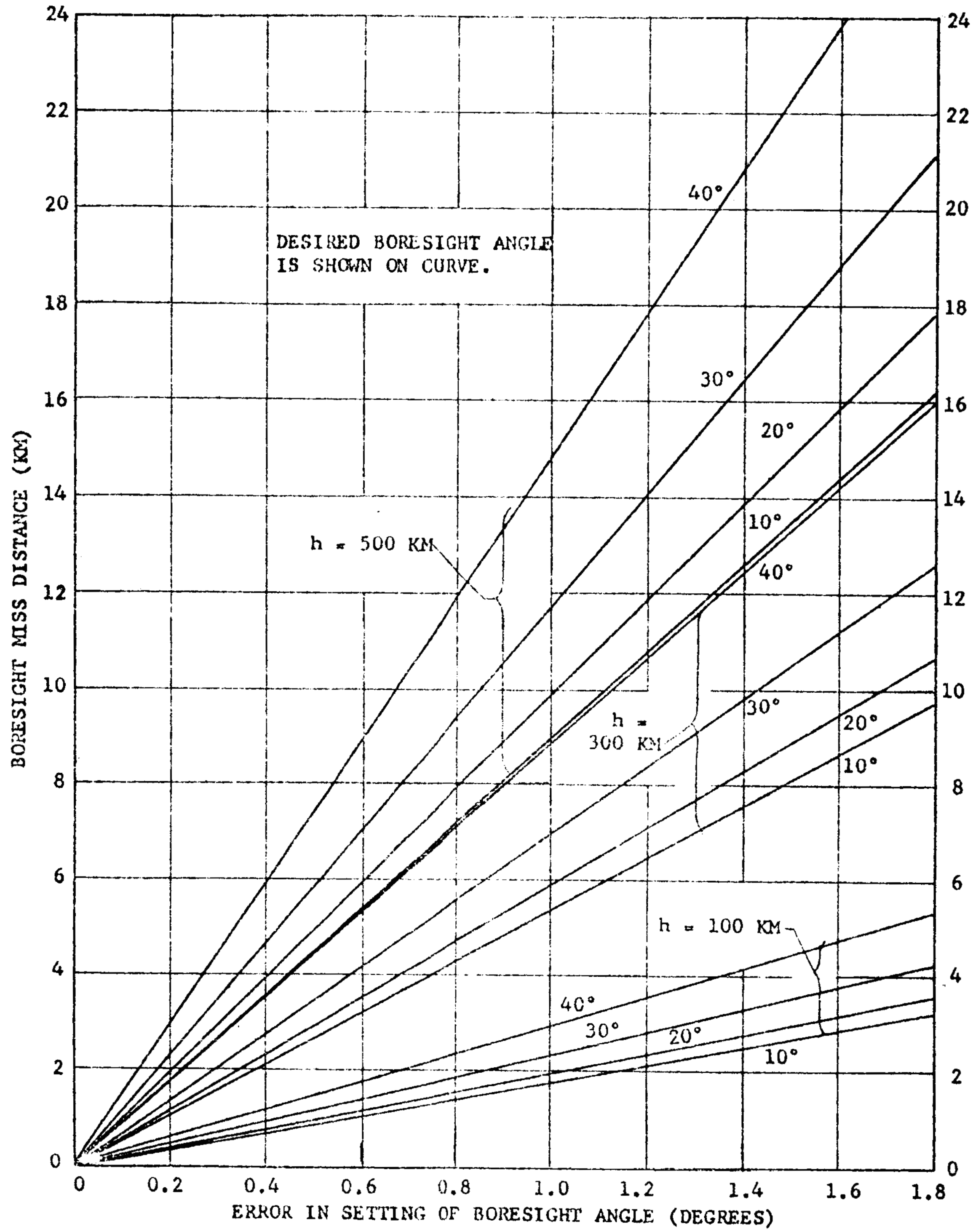


FIGURE 4.12

BORESIGHT MISS DISTANCE (KM)
VS
ERROR IN SETTING OF BORESIGHT ANGLE (DEGREES)

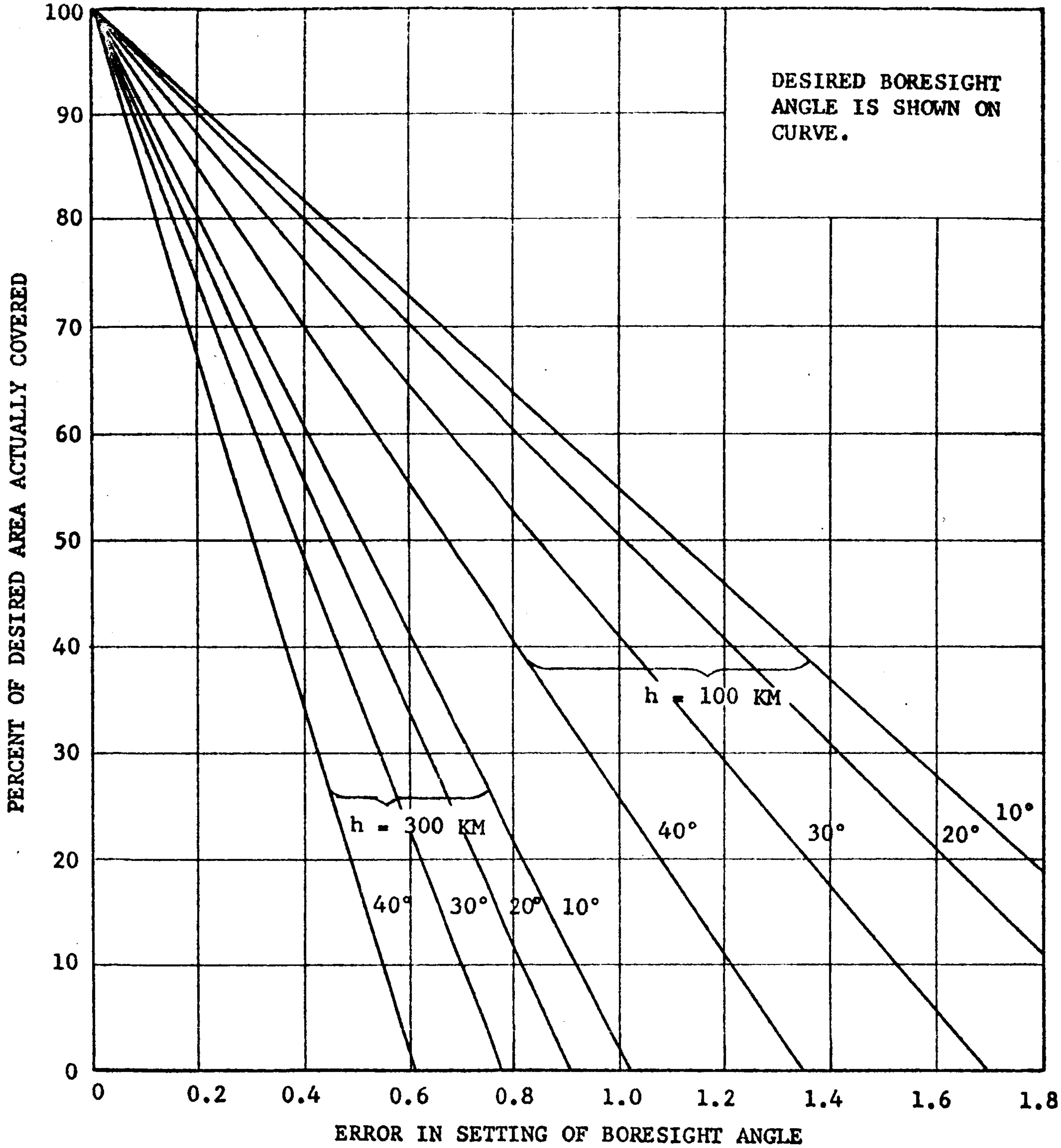


FIGURE 4.13

PERCENT OF DESIRED AREA ACTUALLY COVERED VS.
ERROR IN SETTING OF BORESIGHT ANGLE

Figure 4.14 shows lost area versus altitude instability and again, with reasonable stability, the condition would be intolerable.

Fortunately the same mirror mechanism by which the camera is directed can be utilized to compensate for roll and altitude instability if we assume, not unreasonably, that the near-future attitude and altitude can be predicted with reasonable accuracy from recent history.

Just as the pitch variations had a very small effect on swath width so do they on pointing accuracy. Furthermore, because the pointing angle is perpendicular to the flight line, pointing accuracy is insensitive to yaw.

In summary, tight attitude and altitude control are not required to realize adequate resolution.

Accurate control (or knowledge) of roll and altitude are necessary to ensure efficient high resolution photography.

Under these conditions the values of one degree for pitch and roll stability, two degrees for yaw stability and five percent for altitude stability will be adequate and are used in the exemplary systems.

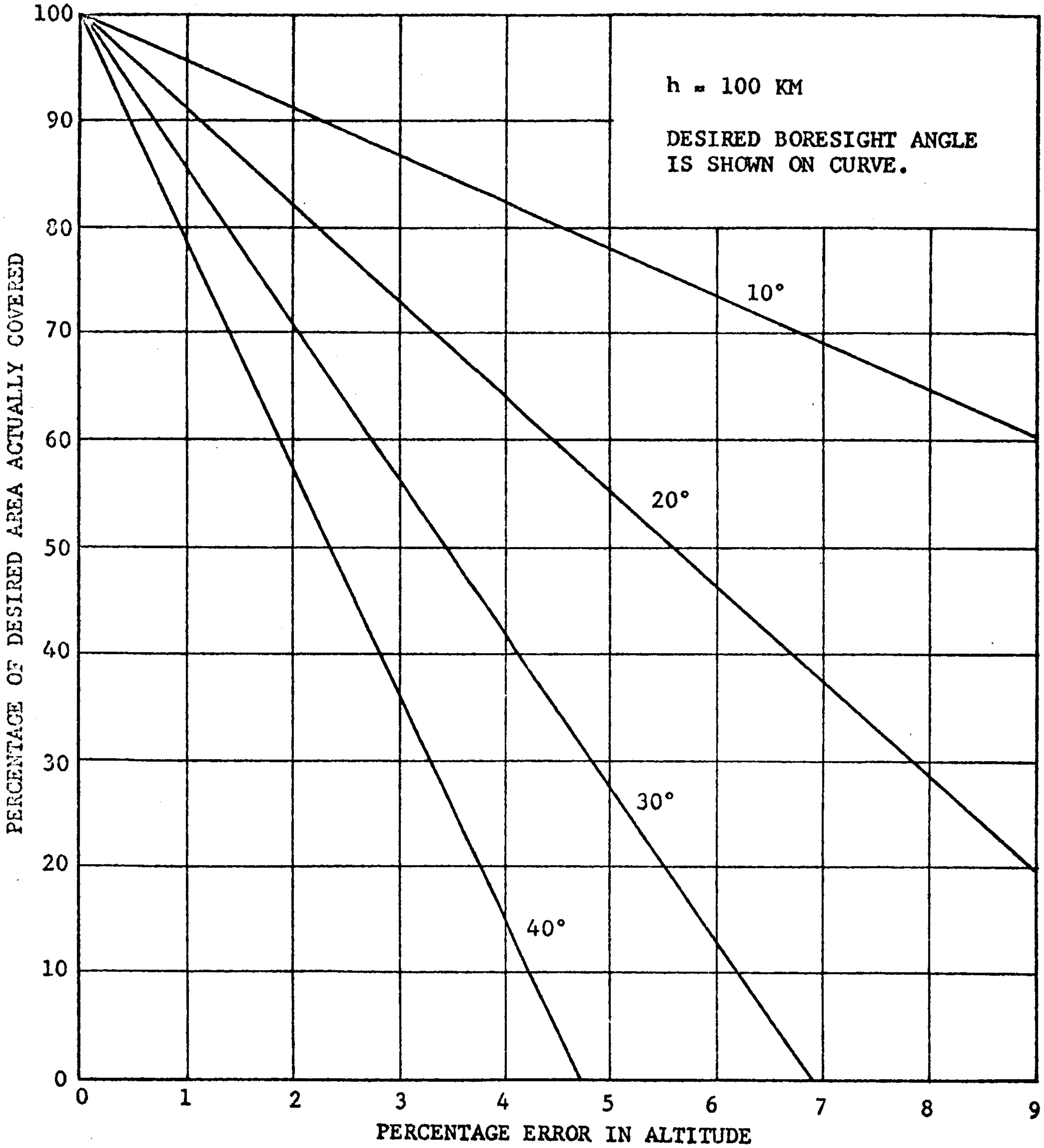


FIGURE 4.14

COVERED AREA VS. ALTITUDE INSTABILITY

4.2 GROUND RESOLUTION VS. FOCAL LENGTH FOR FIBER SYSTEMS

In the cartographic and high acuity systems described in this document the sensor is the vidicon tube. By judicious use of fiber optical elements the area sensitivity of the vidicon is converted to a line sensor for use in the various cameras. It is of interest to examine the ground resolution that can be obtained by this system. For this purpose a set of curves have been prepared to illustrate the lunar surface resolution as a function of camera lens focal length for several altitudes and fiber diameters*.

The emperically determined Kell factor of 1.4, not included in the equation, is included in the curves. This factor relates the number of fibers required to the number of resolution elements actually achieved along a line. The necessity for such a factor can be appreciated by considering the viewing of a checkerboard having elements the same size as the fibers. If the squares and fibers are misregistered by exactly a half fiber, the resulting output will be a uniform gray.

*The simple geometric relation $i/f = g/a$ is used where i is image size, f is focal length, g is ground distance and a is vehicle altitude.

The range of fiber diameters is given from 5 microns to 50 microns; 25.4 microns (μ) = 0.001 inch . The current state-of-the-art in mass production of optical fibers is illustrated by two products, one by American Optical having 20μ fiber diameters and one by Bausch and Lomb having 15μ fiber diameters. Smaller fibers are possible, but these are of questionable merit both from ease of mass fabrication and structural integrity. Furthermore limitations of the vidicon tube in addition to fiber fabrication problems place a lower limit on fiber size. Currently it is planned to utilize vidicons which can adequately read data presented by a 21μ fiber. Attempts to work with vidicon electron beams of smaller diameter than that required for this fiber size will probably result in excessive cross-talk between fibers due to the Gaussian distribution of electrons across the beam of the vidicon.

Figures 4.15 through 4.19 illustrate the relationship between fiber size, ground resolution and focal length.

As shown on Figure 4.15 a focal length of 0.28 meters (11.04 inches) is required for the 10 meter surface resolution system and 2.8 meters (110.4 inches) for the 1 meter resolution system when 20μ fibers are used. A detailed examination of suitable commercial lenses (discussed in other sections) has

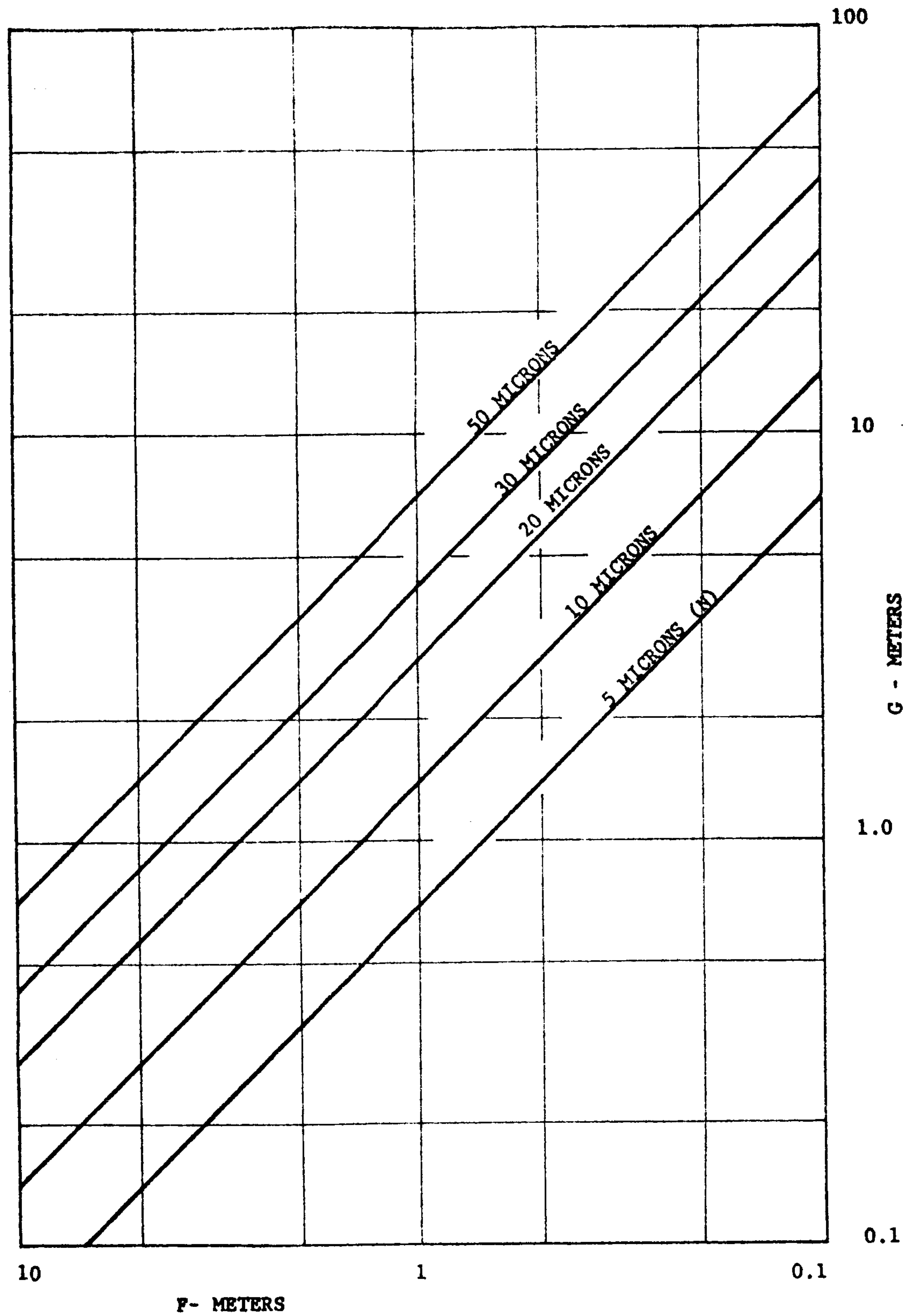


FIGURE 4.15

GROUND RESOLUTION
VS
FOCAL LENGTH
VS
FIBER SIZE AT AN ALTITUDE OF 100 KM

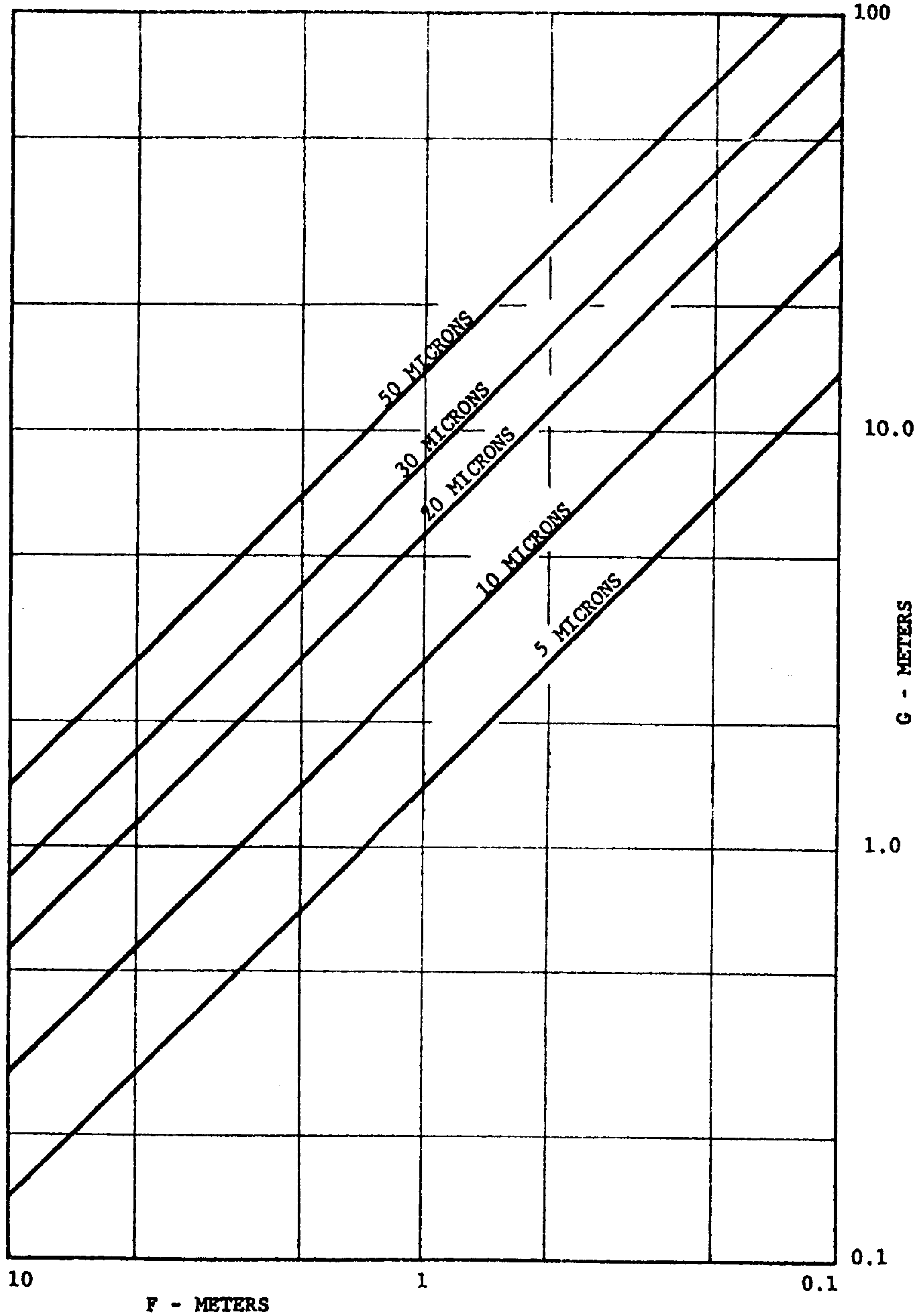


FIGURE 4.16

GROUND RESOLUTION
VS
FOCAL LENGTH
VS
FIBER SIZE AT AN ALTITUDE OF 200 KM

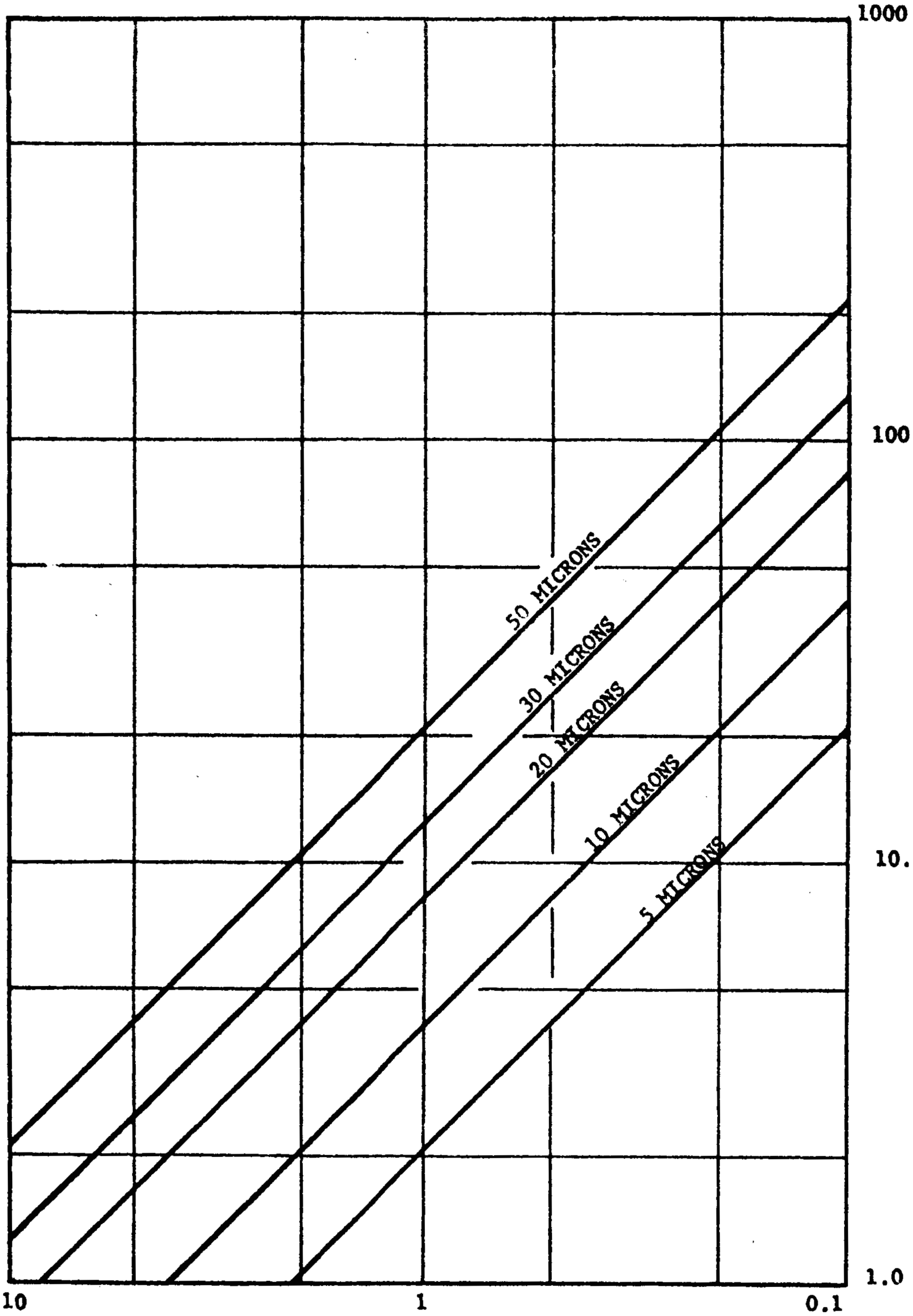


FIGURE 4.17

GROUND RESOLUTION
VS
FOCAL LENGTH
VS
FIBER SIZE AT AN ALTITUDE OF 300 KM

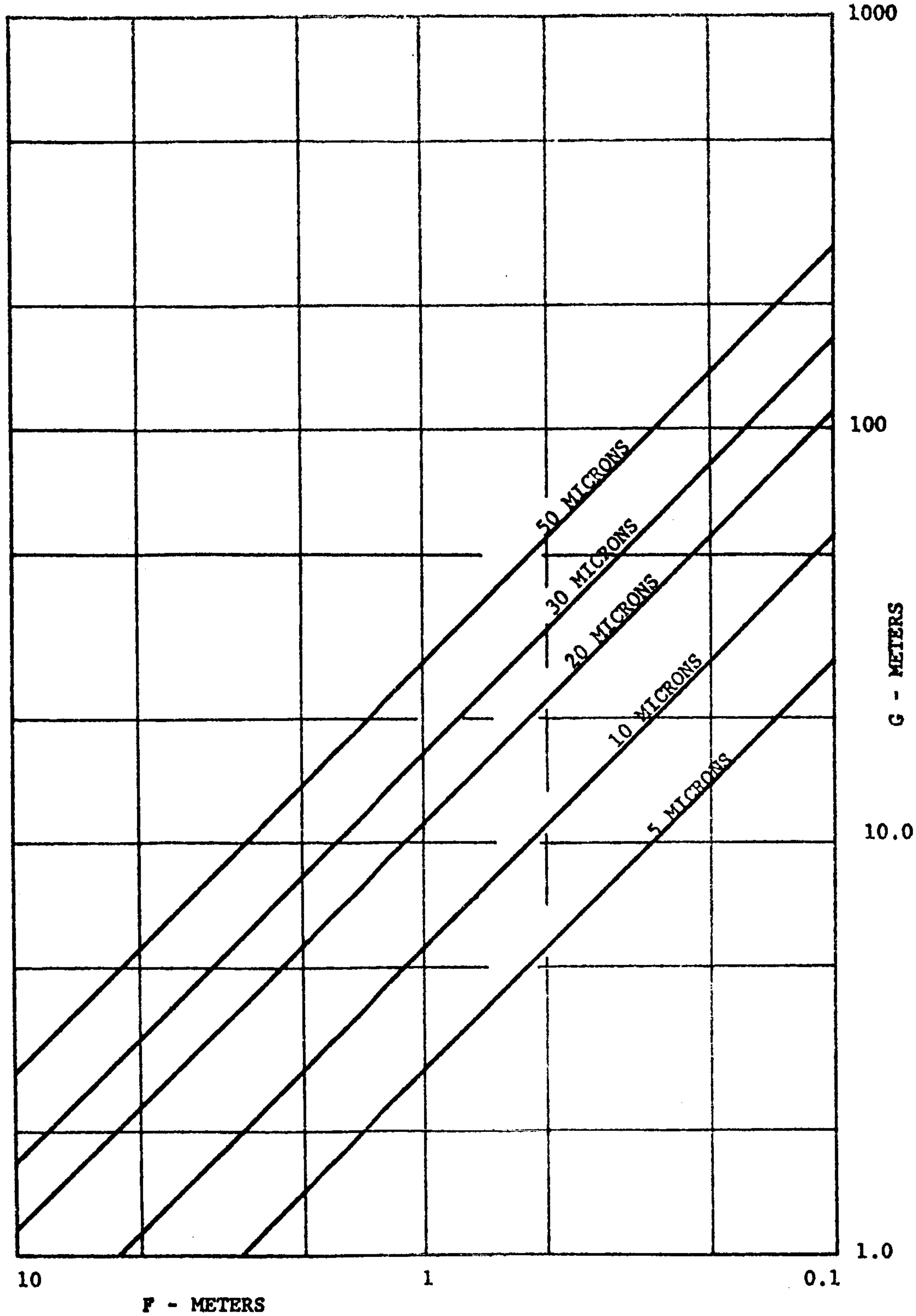


FIGURE 4.18

GROUND RESOLUTION
VS
FOCAL LENGTH
VS
FIBER SIZE AT AN ALTITUDE OF 400 KM

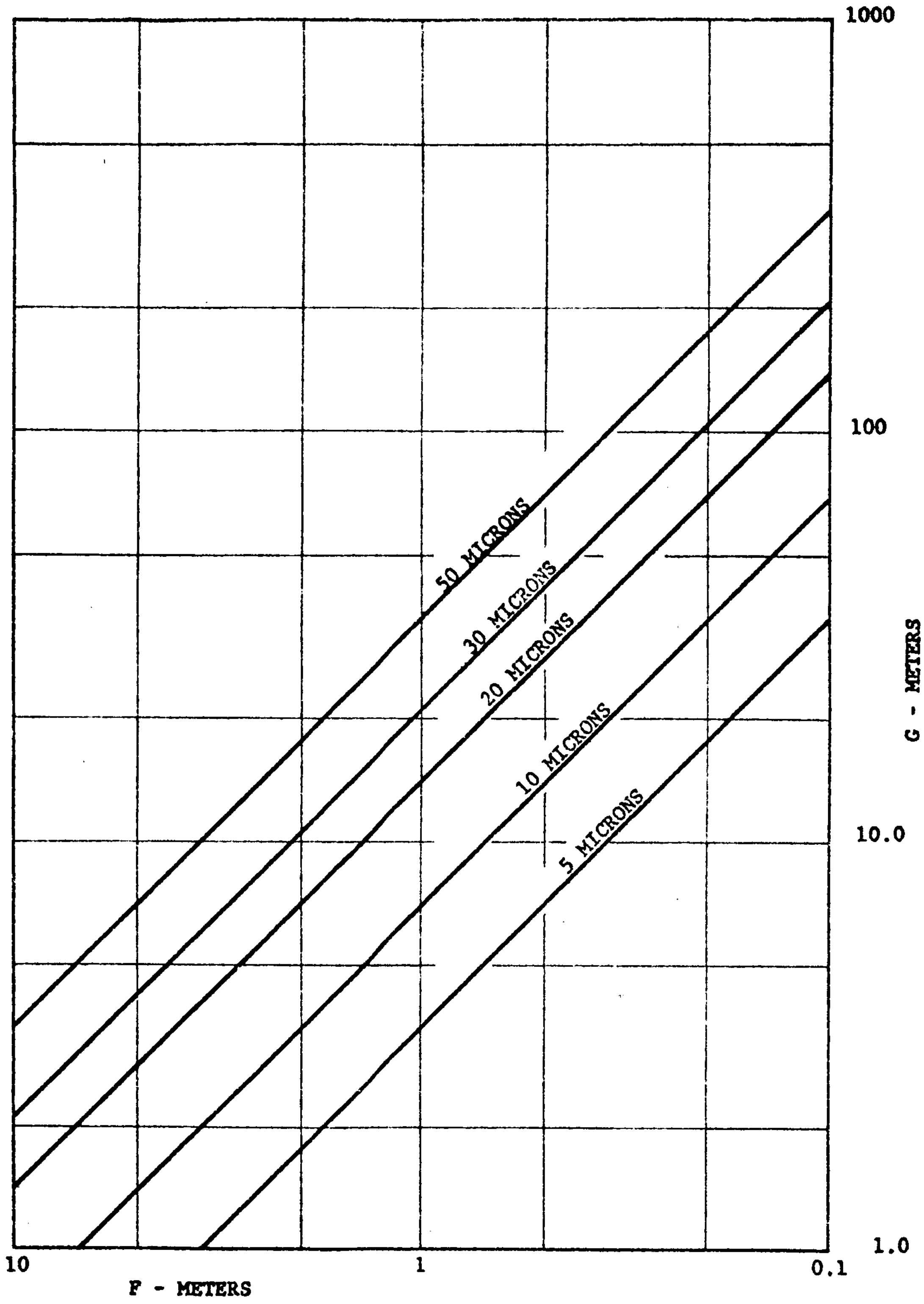


FIGURE 4.19

GROUND RESOLUTION
VS
FOCAL LENGTH
VS
FIBER SIZE AT AN ALTITUDE OF 500 KM

disclosed the availability of 0.305 meter (12-inch) lenses having certain other characteristics highly desirable for the proposed system. Therefore for the illustrative systems discussed in subsequent sections of this document a 12-inch cartographic camera and a 120-inch high acuity camera are developed.

4.3 PRIMARY POWER REQUIREMENTS

It has been pointed out elsewhere that, in the interest of obtaining optimum illumination of the area being mapped, the sun must be essentially in the satellite orbital plane at the center of the mapping period. Hence, during the month of operation the sun will always lie within 15° of the orbital plane, and the periods of available solar energy are essentially constant in both phase and duration. Figure 4.20 shows the percentage of an orbital period (or of the complete mapping operation) for which solar energy will be available. Obviously, the variation with altitude is slight and should not affect the choice of altitude.

If we assume the 100 KM altitude, solar energy will be available for approximately 60 percent of the time and the total energy received in a given time T will be equal to

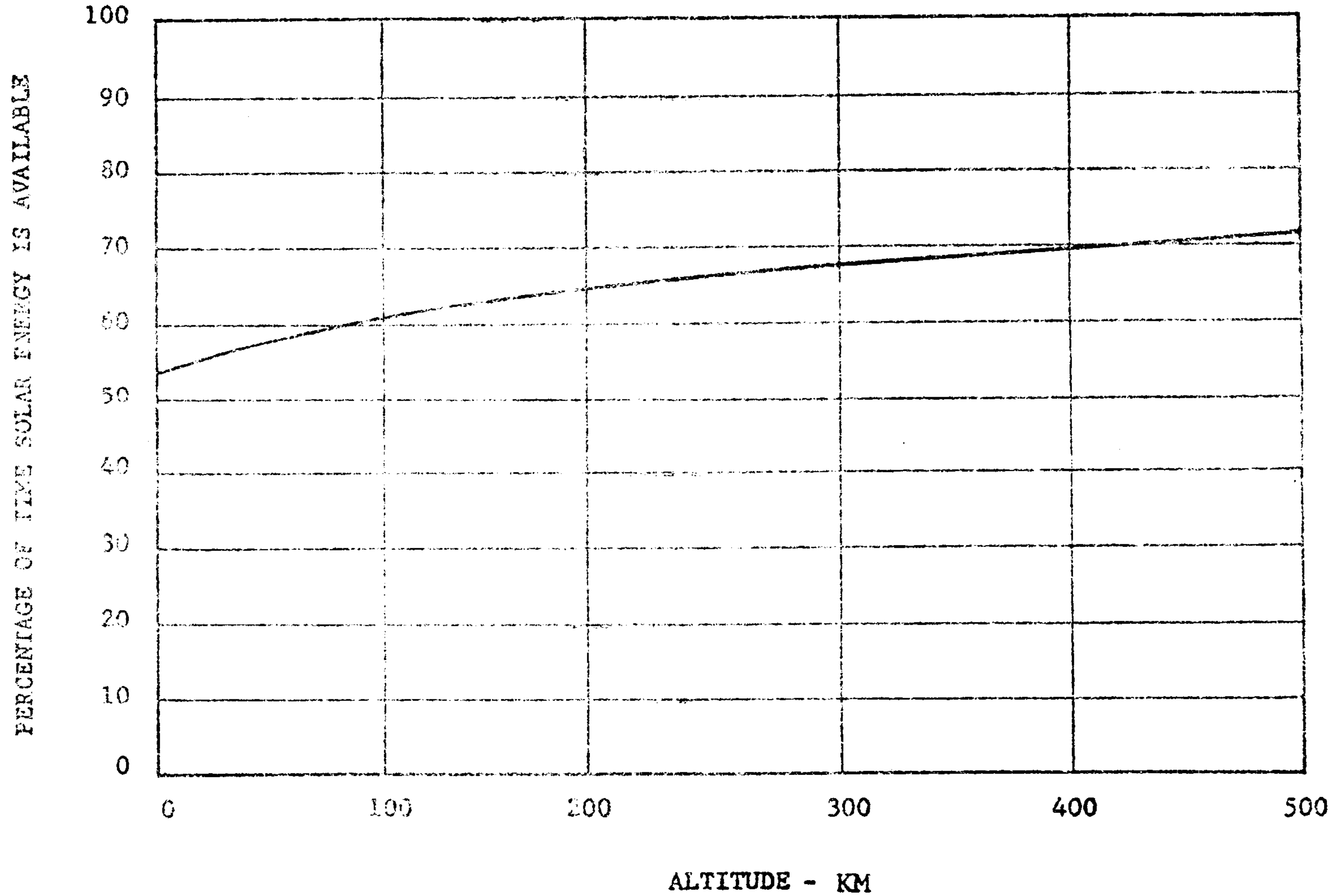


FIGURE 4-20

PERCENTAGE OF ORBITAL PERIOD FOR WHICH SOLAR ENERGY IS AVAILABLE VERSUS ALTITUDE the energy rate (power) per panel multiplied by 0.6T. Letting T_p be the orbital period and W_p be the energy received per period,

$$W_p = .6T_pNP_p$$

where

P_p is the power per panel

N is the number of panels

Power requirements will vary with the phase of the moon, primarily because L.O.S. varies, and it must be assumed that the transmitter will be operated whenever L.O.S. exists. The heaviest loads will occur in the vicinity of first and third quarter when L.O.S. is continuous. During this time, the load will vary slightly from orbit to orbit as a function of the specific equipments being operated. In particular, for those passes where the low resolution mapping is done only for ±60° of latitude, the high resolution camera can be used considerably more, resulting in more video storage and hence more power. Thus, the maximum power requirements must be based on these orbits and can be stated as follows:

$$W_{max} \text{ (per orbit)} = T_p\left[P_{xmit} + 2/3KP_{record\ H.R.} + 2/3P_{read\text{-}out\ H.R.} + 1/3P_{camera\ L.R.} + 2/3KP_{camera\ H.R.}\right] = 0.6T_pNP_p$$

Where

P_{xmit} is the power required by the transmitter

P_{record} is the power required by the recorder

$P_{read\text{-}out}$ is the power required to read out the recorder

K is the ratio of record to read-out time for the high resolution information

Clearing the T_p and setting K equal to .23 and P_p equal to 88 watts the expression becomes:

$$0.6 \times 88N = P_{xmit} + .15P_{record\ H.R.} + .67P_{read\text{-}out\ H.R.} + .15P_{camera\ H.R.} + .33P_{camera\ L.R.}$$

Since the recorders use 60 watts for both recording and reading out and the cameras about 50 watts total we have

$$N = \frac{P_{xmit} + 61}{52.8}$$

Thus, a single panel will almost satisfy all VOIS requirements and the transmitter is essentially the sole factor in determining the number of panels required.

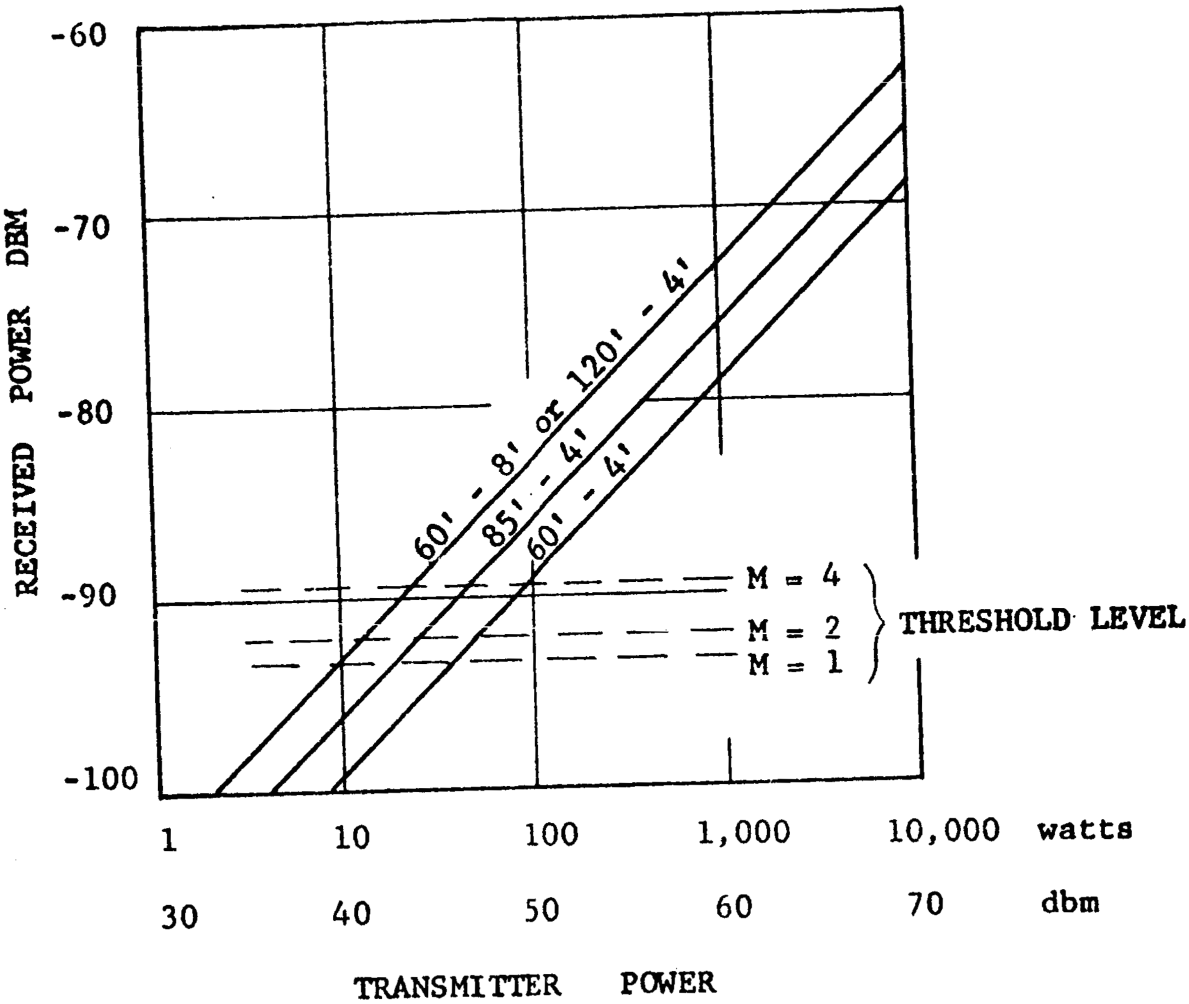
4.4 TRANSMITTER POWER, RESOLUTION AND SIGNAL TO NOISE

Although the VOIS package study does not include the data link, it is of interest to examine the resulting signal-to-noise ratio as a function of ground resolution and transmitter power.

Obviously the data rate (and therefore the width of the baseband) is proportional to the square of the linear ground resolution. For a given modulation type the required bandwidth is directly proportional to the baseband. Hence the establishment of the useable bandwidth permits analysis of appropriate tradeoffs between low and high resolution mapping.

Figure 4.21 shows the signal power received at the earth from a lunar orbiting transmitter at 2300 mcs. The three curves are for three different antenna combinations and the horizontal dotted lines indicate receiver threshold for various indices of frequency modulation using the best known estimate of noise power received due to lunar temperature.

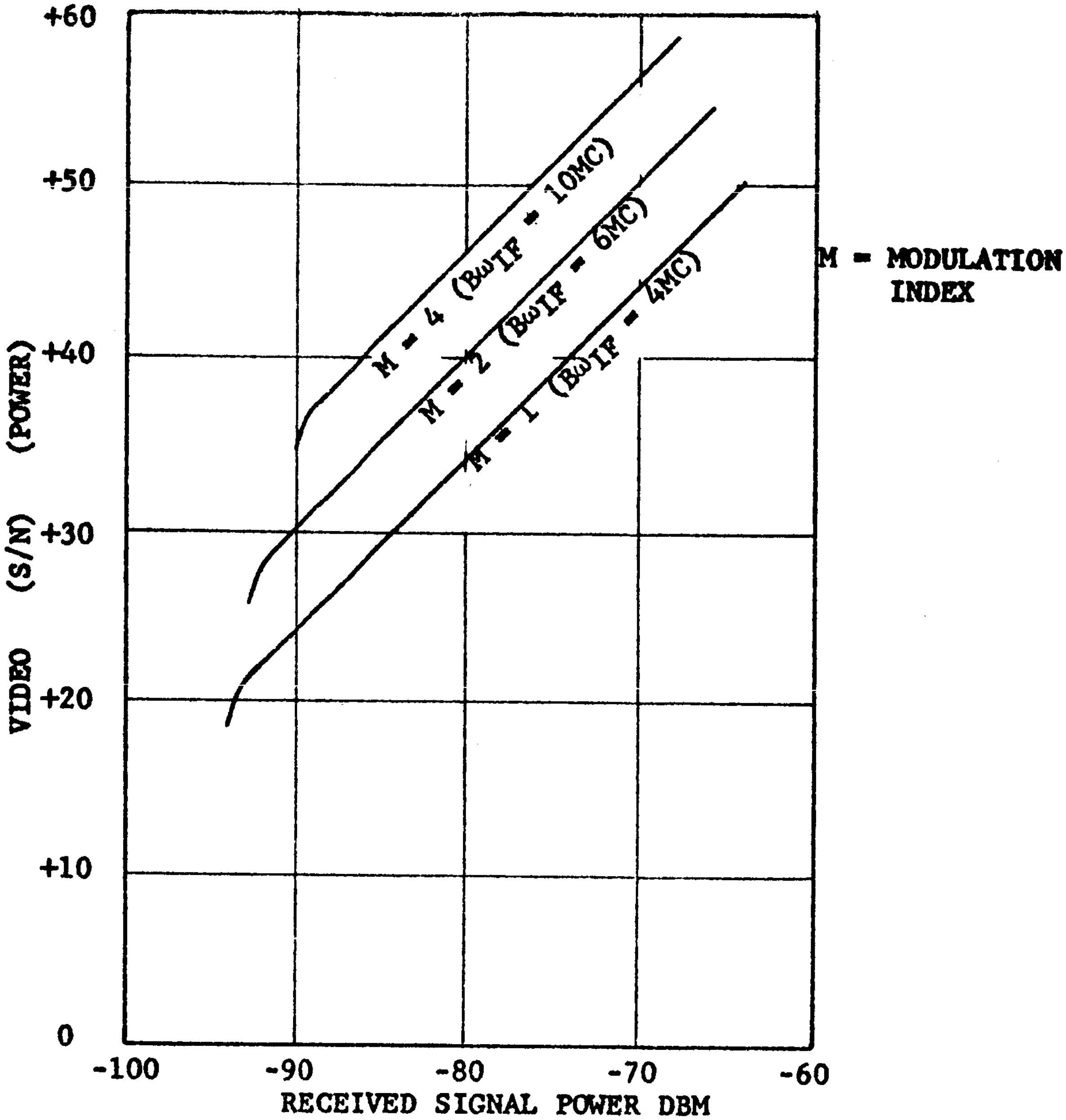
Once the received power is established reference to Figure 4.22 shows the resulting video signal-to-noise ratio, again



CONDITIONS
f = 2,300 miles
D = 250,000 miles
T.L. = 2 db losses
T = 441°K System Noise

FIGURE 4.21

SIGNAL POWER RECEIVED AT THE EARTH FROM LUNAR ORBITER AT 2,300 MCS



CONDITIONS:
1MC VIDEO BANDWIDTH
441°K SYSTEM NOISE TEMPERATURE
IF BANDWIDTH = 2 f_{max} (1+M)
f_{max} = MAX MODULATING FREQUENCY

FIGURE 4.22

VIDEO S/N RATIO VERSUS RECEIVER SIGNAL POWER for several modulation indices. It will be noted that the higher the index, the better the S/N ratio, but the threshold also is increased. This simply means that there is less room for fading without complete loss of signal. Another result of a high index is a greater i.f. bandwidth, but it is presumed permissible to tap off the receiver ahead of the i.f. and provide a separate wideband i.f. circuit for the video.

In employing these curves a number of things must be kept in mind. For example transmitter power may be reduced if we utilize a larger antenna at the vehicle. Thus we reduce solar panel area and add antenna area. Furthermore, we increase antenna pointing problems in the satellite. Very large earth-based antennas may also cause pointing problems especially if the satellite is close to the earths horizon as shown as Figure 4.23. Another group of related factors involve S/N and resolution. As resolution is increased, bandwidth increases and S/N ratio falls off. Ultimately resolution (or small area contrast) suffers because of noise and the calculated resolution is not realized. Also S/N ratio appears to increase if we eliminate the higher order (low energy) sidebands in an f.m. system, but modulation distortion (which is another type of "noise) increases and again the computed resolution is not achieved. Finally there is

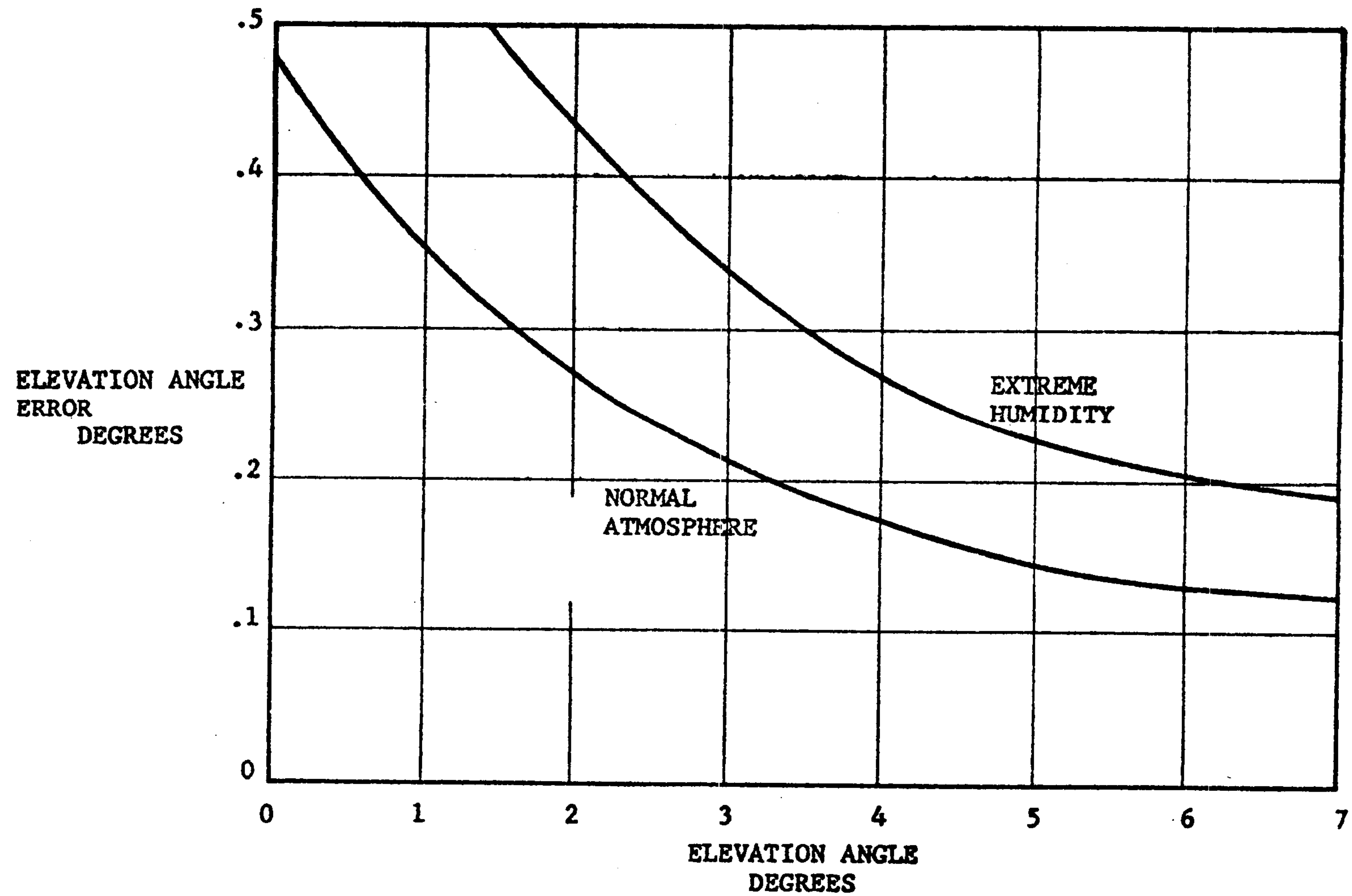


FIGURE 4.23

REFRACTIVE POINTING ERROR VS. ELEVATION ANGLE (TARGET RANGE 1000 N.M.)

no point in establishing a S/N ratio greatly in excess of that delivered by the camera, i.e., 30 to 35 db.

Although fading is not anticipated to be a serious problem, some fading will certainly exist immediately prior to satellite occultation and immediately after reappearance. Accordingly, the system should not be operated too close to threshold.

Taking all these factors into account and referring to the curves, it will be seen that a 100 watt transmitter feeding a four foot antenna will deliver - 86 dbm through an 85' dish to the receiver. A -86 dbm signal having a modulation index of 2 will provide a 34 db S/N signal out of the receiver and a fade margin of about 6 db will be permissable. This represents just about acceptable operation. If however, a 250 watt transmitter is available the resulting S/N will be 37 db and a fade margin to threshold of 9 db is obtained.

By using a separate i.f. amplifier having a bandwidth of 6 mc this would appear to provide a close-to-optimum compromise.

4.5 PHOTOGRAPHIC SYSTEM PARAMETERS

The feasibility of completely photographing the moon in one lunar month plus rephotographing selected areas of interest utilizing conventional photographic techniques is being considered in addition to the fiber optical vidicon system. It is entirely possible to do the task photographically. However, the interaction of system parameters not under the control of the experimenters, such as satellite period and distances between equatorial crossings (walk distance), combined with film format size unfortunately constrain many of the photographic parameters. It will be seen that these imposed limitations result in some non-optimum configurations from the consideration of photographic scale and lunar surface resolution.

4.5.1 Film Formats

Experience in automatic, self-contained film processing units has shown that film in excess of 5 or 6 inches is difficult to handle due to the size and weight of materials and equipment especially when considering a 30 day operation. Therefore, the two formats considered initially will be limited to 70mm and 5 inch film. Due to sprocket perforations and allotment of a small area along the edge for recording ancillary data (such as time and altitude), the actual pictorial area is limited to 50mm on the 70mm film and 4.5 inches on the 5 inch film. It is onto these widths that the lens must image the specified ground swath. Since the format and ground swath widths are fixed, choice of vehicle altitude, also, defines focal length by the following relation:

$$\frac{\text{film format width}}{\text{camera focal length}} = \frac{\text{lunar surface swath width}}{\text{altitude}}$$

This relationship is derived from the similar triangles for the camera interior geometry and system exterior geometry (see Figure 4.9).

4.5.2 Fore/Aft And Sidelap Stereoscopic Mapping Modes

Two separate stereo configurations are examined. The first is the fore/aft technique (see Figure 4.9) where the dual coverage required for stereoscopic photo coverage is obtained with a forward and an aft "look" through the same lens. This configuration has constant depth sensitivity. The width of the ground swath viewed at any given altitude is taken as γ times the distance between orbital crossings of the equator (walk distance or W.D.). This γ factor is determined to give an adequate amount of sidelap between passes.

As is shown in the parametric study on attitude and altitude control, the required swath width redundancy to insure a minimum of 5% overlap between passes becomes quite large for vehicles at higher altitudes. With a reasonable set of control parameters (roll and pitch = $\pm 1°$, yaw = $\pm 2°$ and H = $\pm 5\%$)* the following swath width coverages are required:

Fore/Aft Configuration

Vehicle Altitude in Kilometers	Required Coverage Swath in Kilometers	"ψ" Percent Initial Walk Distance
100	40	125%
200	47.5	134%
300	55	144%
400	63	157%
500	71	161%

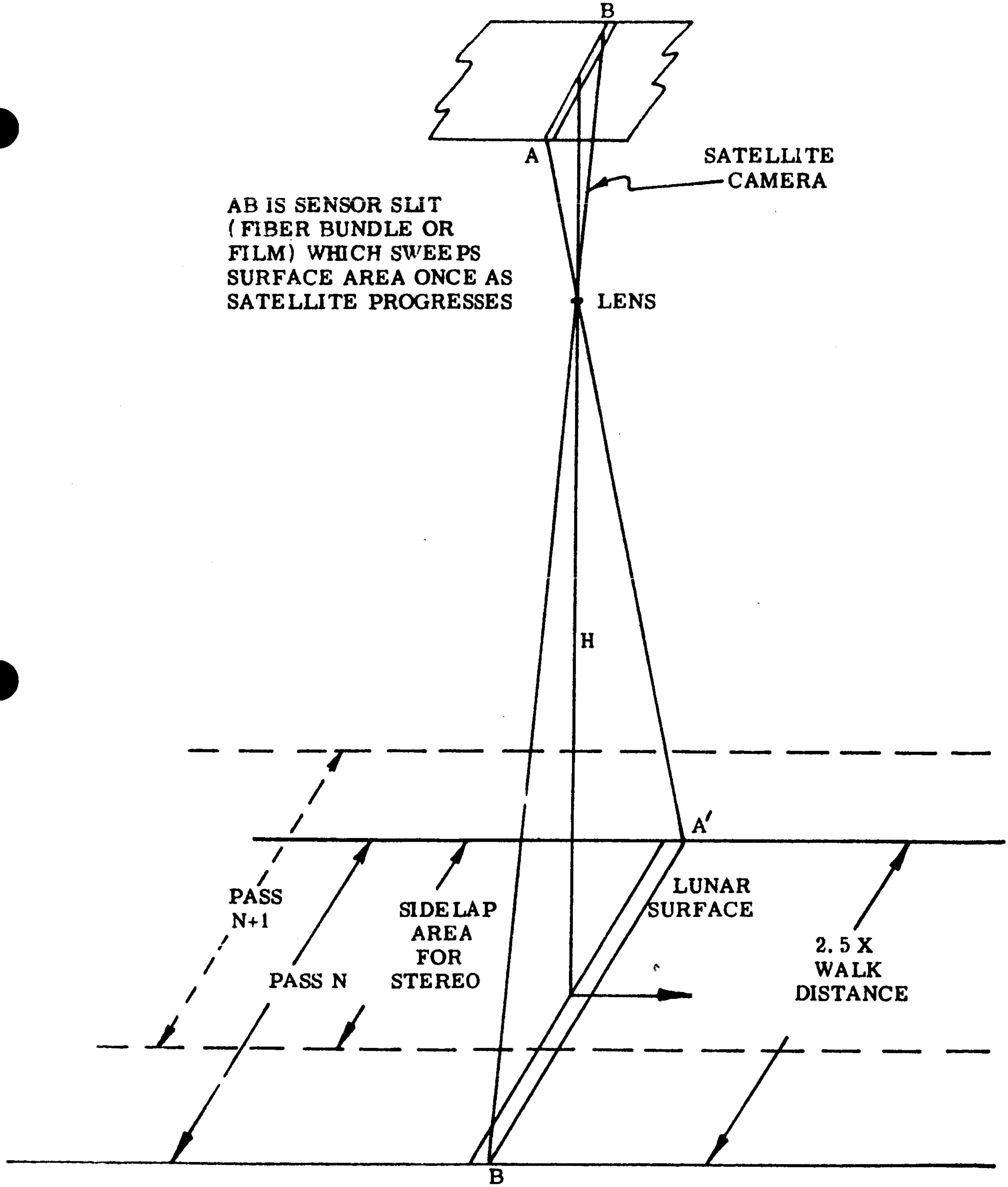
With the fore/aft configuration the swaths are seen twice, once by the forward and once by the aft look.

*All further calculations of film weight or format width take these attitude and altitude variations into consideration.

The necessity of extra capacity for the required coverage redundancy at higher altitudes suggests that operation at low vehicle altitudes is the most advisable. Higher altitude operation also contributes significantly to other design problem areas discussed elsewhere in the document.

The second stereoscopic camera configuration considered is illustrated in Figure 4.24 and incorporates sidelap between adjacent passes to give redundant coverage for stereoscopic measurements. The depth sensitivity of this system varies as a function of lunar latitude (see Figure 4.6). The width of the surface swath to be imaged upon the film is 2.5X the required swath coverage (including correction for attitude and altitude control).

The following coverage swath widths are dictated by the previously illustrated attitude and altitude control factors:



SIDELAP STEREO CONFIGURATION

FIGURE 4.24

Sidelap Configuration

Vehicle Altitude In Kilometers	Minimum Swath Width In Kilometers	Sidelap Stereo Swaths In Kilometers	Percent Initial Walk Distance
100	40	100	304%
200	47.5	119	335%
300	55	138	360%
400	63	158	385%
500	71	178	404%

It can be seen by referring to the last two charts that the fore/aft camera configuration is far more economical in film consumption.

The fixing of lunar surface swath width to be photographed (which is γ times walk distance) orbital height and film format size is sufficient to specify lens focal length. As can be seen from similar triangles in Figure 4.24.

$$\frac{AB}{f} = \frac{A'B'}{H}$$

where

f = focal length

AB = image width on film (50 mm or 4 1/2 inches)

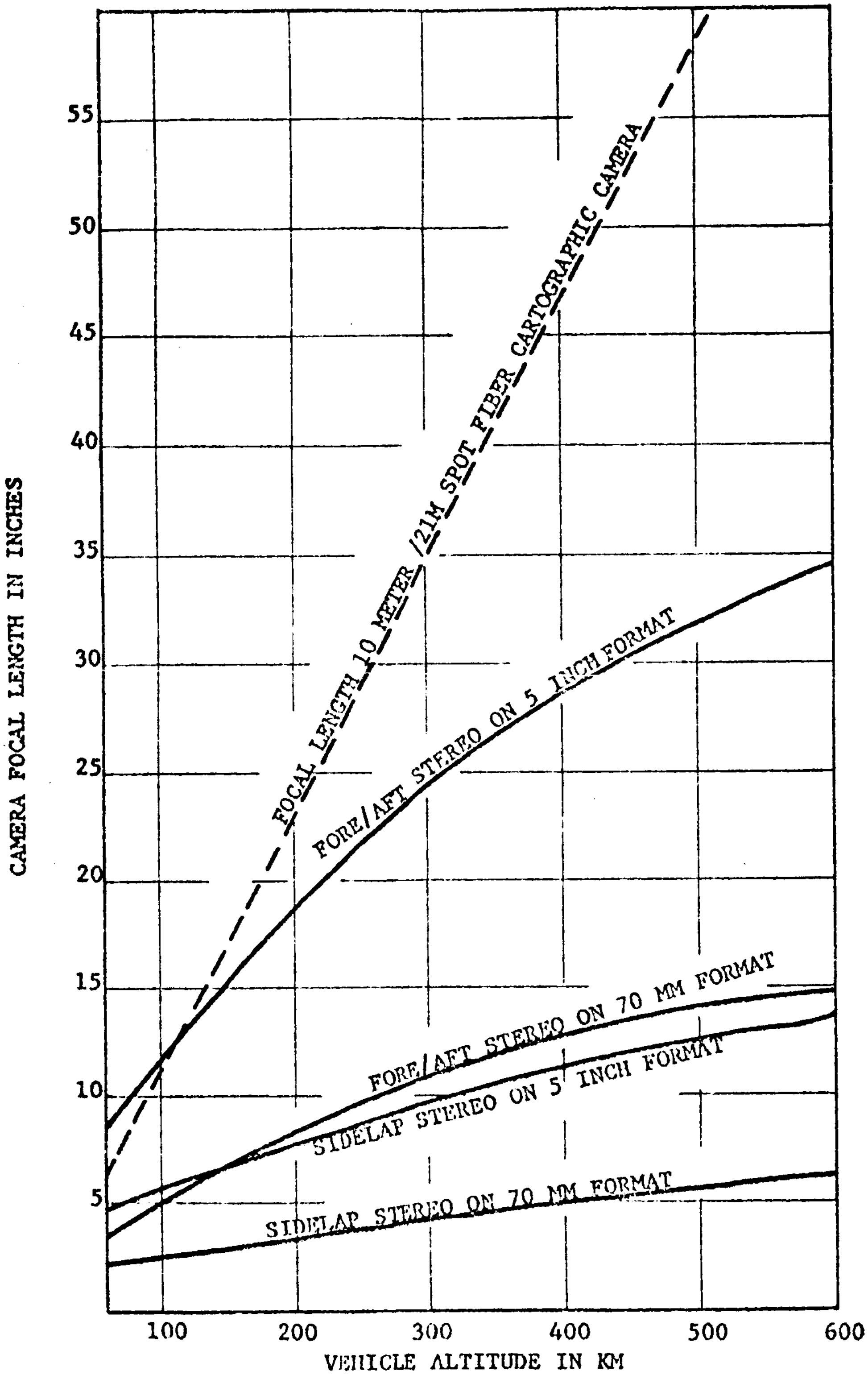
H = vehicle altitude

$A'B'$ = ground swath to be photographed

Figure 4.25 illustrates this relationship between required camera lens focal length and vehicle altitude for the 70mm and 5 inch film. These focal lengths can readily be compared to the focal length required for lens for the fiber optical camera by referring the dashed line in the same figure. It is necessary to note that the independence of total image width when considering the fiber sensor allows one to hold the photographic scale constant at a specified value; i.e., choose the lens that images a fixed surface element upon the optical fiber. This situation does not exist in the case of the film sensor since the format width is fixed by the film dimensions. In this case scale will not remain constant but will vary between limits. This will be quite important in subsequent referrals to weight diagrams since the range of permissible scales is limited by system parameters.

The photographic scales fixed by the parameters are determined as follows:

$$\text{Scale} = \frac{AB}{A'B'} = \frac{\text{Actual Camera Format Width}}{\text{Surface Swath Width}}$$



CAMERA LENS FOCAL LENGTH REQUIRED TO IMAGE SPECIFIED SURFACE AREA ON VARIOUS FILM FORMATS WITH FORE/AFT AND SIDELAP STEREO CONFIGURATIONS.

FIGURE 4.25

70MM FORMAT SCALE

Vehicle Altitude Kilometers	Fore/Aft Stereo	Sidelap Stereo
100	1:800,000	1:2,000,000
200	1:950,000	1:2,380,000
300	1:1,100,000	1:2,760,000
400	1:1,260,000	1:3,160,000
500	1:1,420,000	1:3,560,000

5 INCH FORMAT SCALE

Vehicle Altitude Kilometers	Fore/Aft Stereo	Sidelap Stereo
100	1:350,000	1:876,000
200	1:417,000	1:1,040,000
300	1:482,000	1:1,210,000
400	1:561,000	1:1,390,000
500	1:622,000	1:1,560,000

It is reiterated that these scales are not arbitrarily chosen but rather imposed by system parameters. It is significant to contrast these scales with the scale of the fiber optical unit which remains fixed at 1:330,000, a value chosen to allow observation of a 10 meter lunar surface element regardless of vehicle height.

4.5.3 Lunar Surface Resolution Photographic System

The resolution of photographic systems in general exceeds the resolution of electronic read-out devices used to convert the photographic data to video pulses. Therefore, the system resolution was taken as that attainable using a flying spot scanner or vidicon tube with a 21μ spot size. This value is felt to be a good median for direct read-out systems on formats up to 6 inches wide. Systems have been designed to read-out with small spot diameters using optical minification of the spot. Due to limitations on the length of line that can be operated by cathode ray tubes with 21μ beam diameters, optical minification techniques have been forced to rely upon complex procedures of optical segmentation which require moving optical elements in the vehicle. These techniques also result in problems of subsequent ground reconstitution of imagery that are quite complex. For the sake of long term reliability it is desirable to keep moving parts in the vehicle to a minimum. Subsequent discussion will be directed towards determining the feasibility of optical minification using a fiber optical line scan generator having no moving parts.

Lunar surface resolution is determined in the following manner:

For 70mm film which has 50mm of image width:

$$\text{Resolution cells} = \frac{50\text{mm}}{21\mu} = 2380$$

For 5 inch film which has 11.4 centimeters of image width:

$$\text{Resolution cells} = \frac{11.4 \text{ centimeters}}{21\mu} = 5420$$

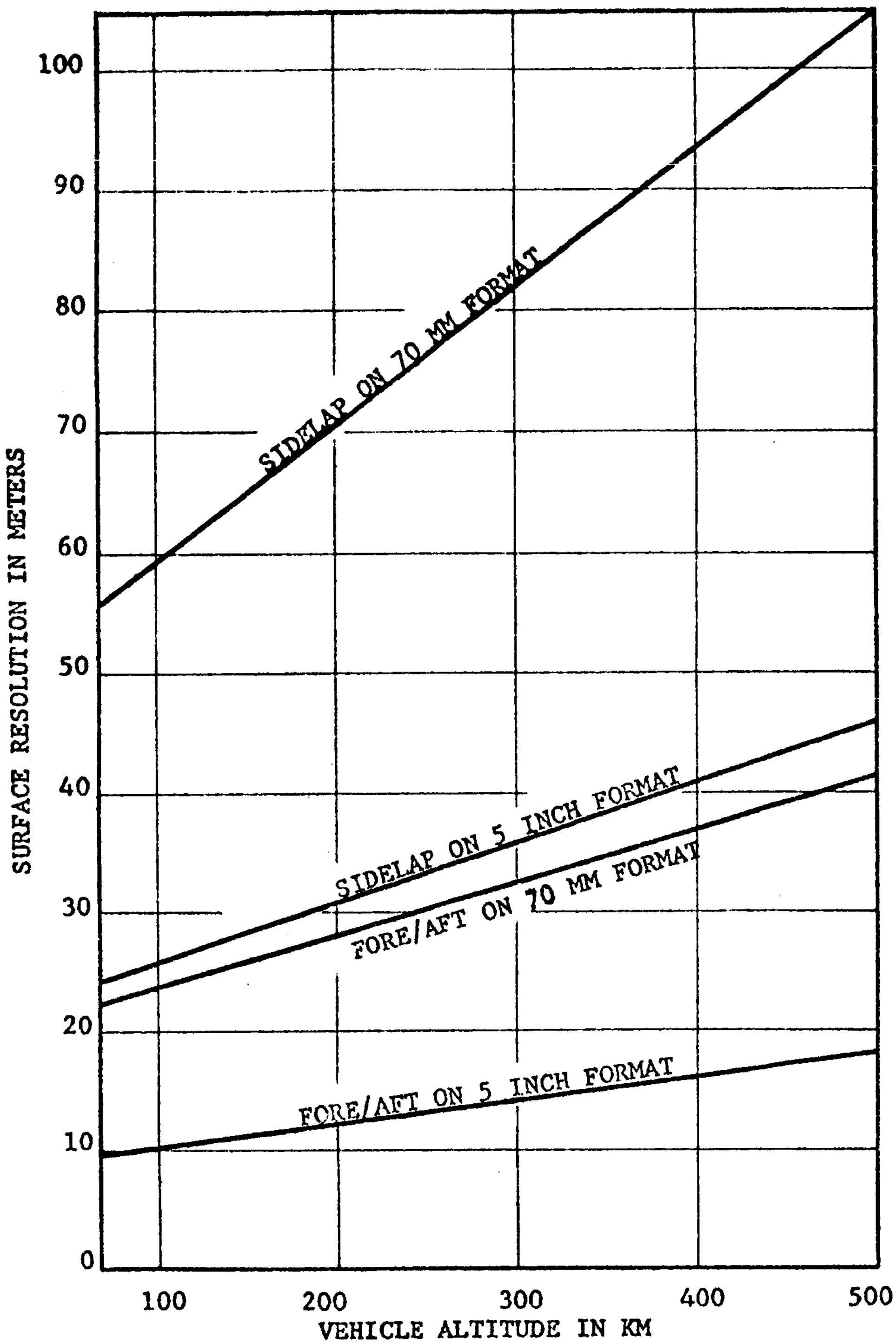
$$\text{Lunar surface resolution} = \frac{\text{surface swath width}}{\text{resolution cells}} \times 1.4$$

Where 1.4 is the Kell factor

This data is summarized in Figure 4.26 for both fore/aft and sidelap stereo configuration using 70mm and 5 inch film.

4.5.4 Photographic Processing Techniques

Fairchild Camera and Instrument Corporation has designed, developed and fabricated several automatic high acuity film processing units for use in reconnaissance drones. The results of this work suggest the following materials and techniques to be applicable to the lunar orbiter program.



LUNAR SURFACE RESOLUTION FOR
SIDELAP AND FORE/AFT STEREO
MAPPING CONFIGURATIONS USING
70 MM AND 5 INCH FILM FORMATS.

FIGURE 4.26

Thin base photographic films (for weight saving) capable of resolution well in excess of that required for the lunar orbitor program and having sufficient photographic speed and excellent physical and photographic characteristics for cartographic work in the lunar environment are available in 70mm and 5 inch widths. In addition 12 inch film may be cut and perforated for the special requirement discussed later. This material can be readily processed to a good quality transparency suitable for video scanning using a monobath development procedure. The use of a monobath eliminates the requirement of storing, applying and washing out the traditional processing set of developer, short stop and fixer.

The processor for 5 inch film weighs approximately 100 pounds and requires just under 200 watts of power to operate its pumps, heaters and film transport mechanisms. A similar unit for 70mm film would weigh 80 pounds and require approximately 150 watts. One processor would be required for each film strip used. In the case of the fore/aft stereo configuration, two processors would be required for the 5 inch units. For 70mm fore/aft stereo the lenses could be arranged to image their surface detail side by side on a 5 inch film thus requiring only one processor. The high acuity camera requires its own processor.

The technique used in the Fairchild units is to apply the monobath processing chemical which is in the form of a very viscous material to the emulsion side of the exposed film and to immediately apply a layer of 1 to 2 mil transparent saran over the viscous developer. This results in a dry sandwich that can be rolled up, drawn through scanners etc., without having processing chemicals interfere. Conveniently this technique does not require drying after processing. The sandwich is fed into a slack box to give sufficient delay between the monobath application station and the video read-out stations to insure complete and proper film processing. The film is read-out through the saran which introduces no problems. Once processed and read-out the film is rolled up for storage. At the resolution levels contemplated a maximum of 10 minutes delay in the slack box will insure adequate processing provided the temperature is controlled to 68°± 2°F. This time lag between application of processing materials and video read-out can be shortened at the slight expense of photographic resolution.

Weights of materials required are as follows:

Thin Base Photographic Film	=	10.85×10^{-3} gms/cm^2
Monobath process chemicals	=	3.55×10^{-3} gms/cm^2 of film
Saran (1.5 mil)	=	5.49×10^{-3} gms/cm^2 of film
Total to take, process and store photographic detail	=	1.989×10^{-3} gms/cm^2
		Or 0.438 lbs/meter^2

The thickness of the resulting sandwich is:

Film	0.004
Monobath	0.002
Saran	0.0015
Total	0.0075 inches or 0.191mm

Subsequent calculations of material weight will be made as follows:

$$W = \frac{\text{Area photographed (square meters)}}{(\text{photographic scale})^2} \times 0.438 \text{ lbs/meter}^2 \times K$$

where the K allows for the excess film that is required for any given format width due to margins, etc.

For 70mm film $\quad K = \frac{70}{50} = 1.4$

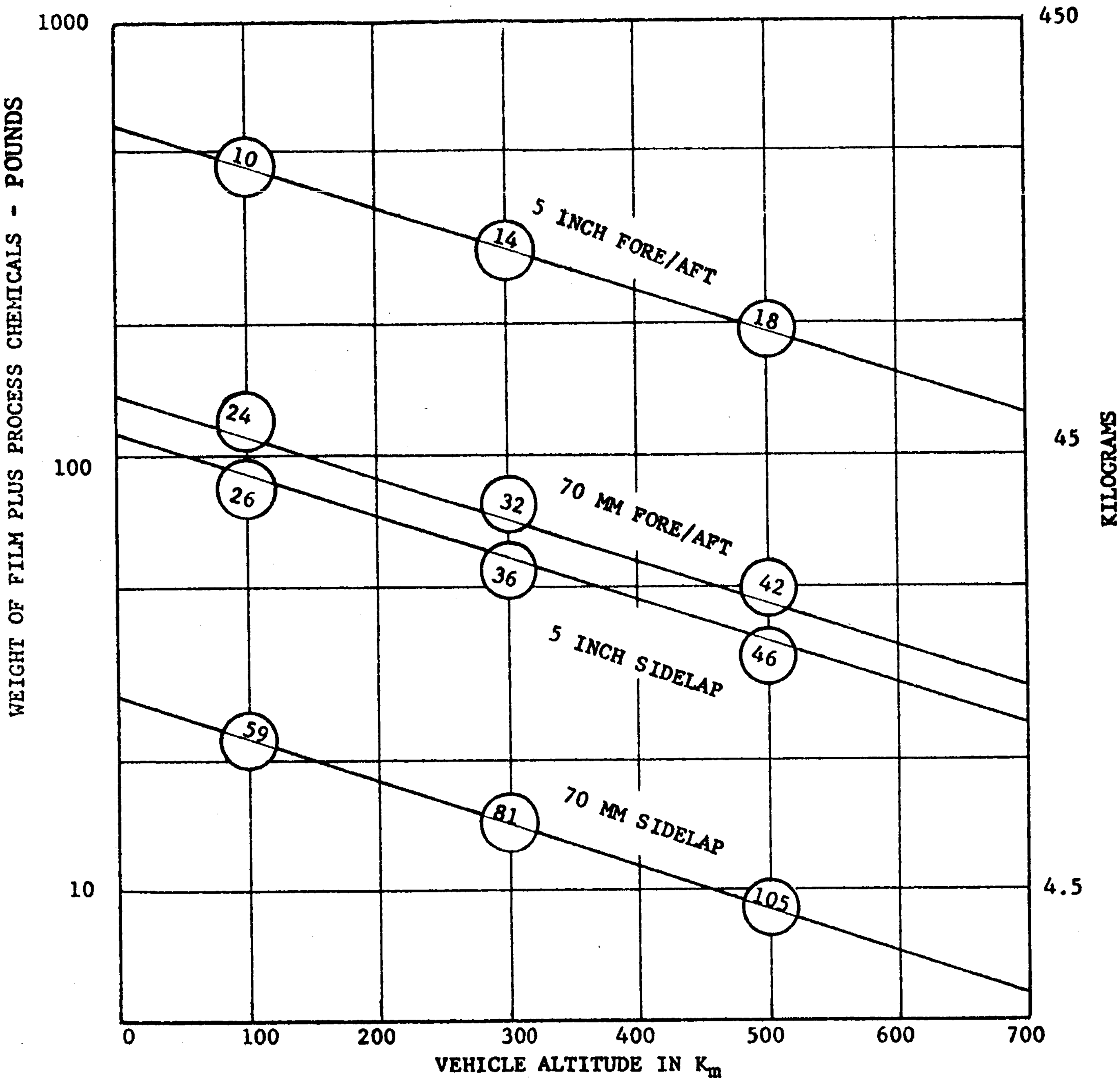
For 5 inch film $\quad K = \frac{5}{4.5} = 1.11$

NOTE: 70mm film makes 50mm available for photo detail and 5 inch film allows 4.5 inches.

4.5.5 Weight of Photographic Materials

Calculations of weight of photographic materials are based upon the minimum film required to map the lunar surface with stereoscopic coverage. A redundancy figure due to the finite swath width of camera coverage must be incorporated. This is illustrated in Figure 4.27. Ideally all camera swaths should get narrower as the cosine of latitude. However, cameras do not operate in this manner at present. Therefore as one approaches the poles the sidelap between adjacent passes gets larger. In an attempt to minimize this added redundancy a trajectory program is suggested that begins and terminates photography at 60° and 76° latitude with the following program (see section 3.3):

pass n	-	pole to pole
pass n + 1	-	+60° to -60°
pass n + 2	-	+76° to -76°
pass n + 3	-	+60° to -60°
pass n + 4	-	pole to pole
etc.,		



Weight of film plus process materials vs. altitude of vehicle for 5 inch and 70 mm film photography of the lunar surface. Encircled values are surface resolutions in meters with the indicated mapping configuration at the various altitudes.

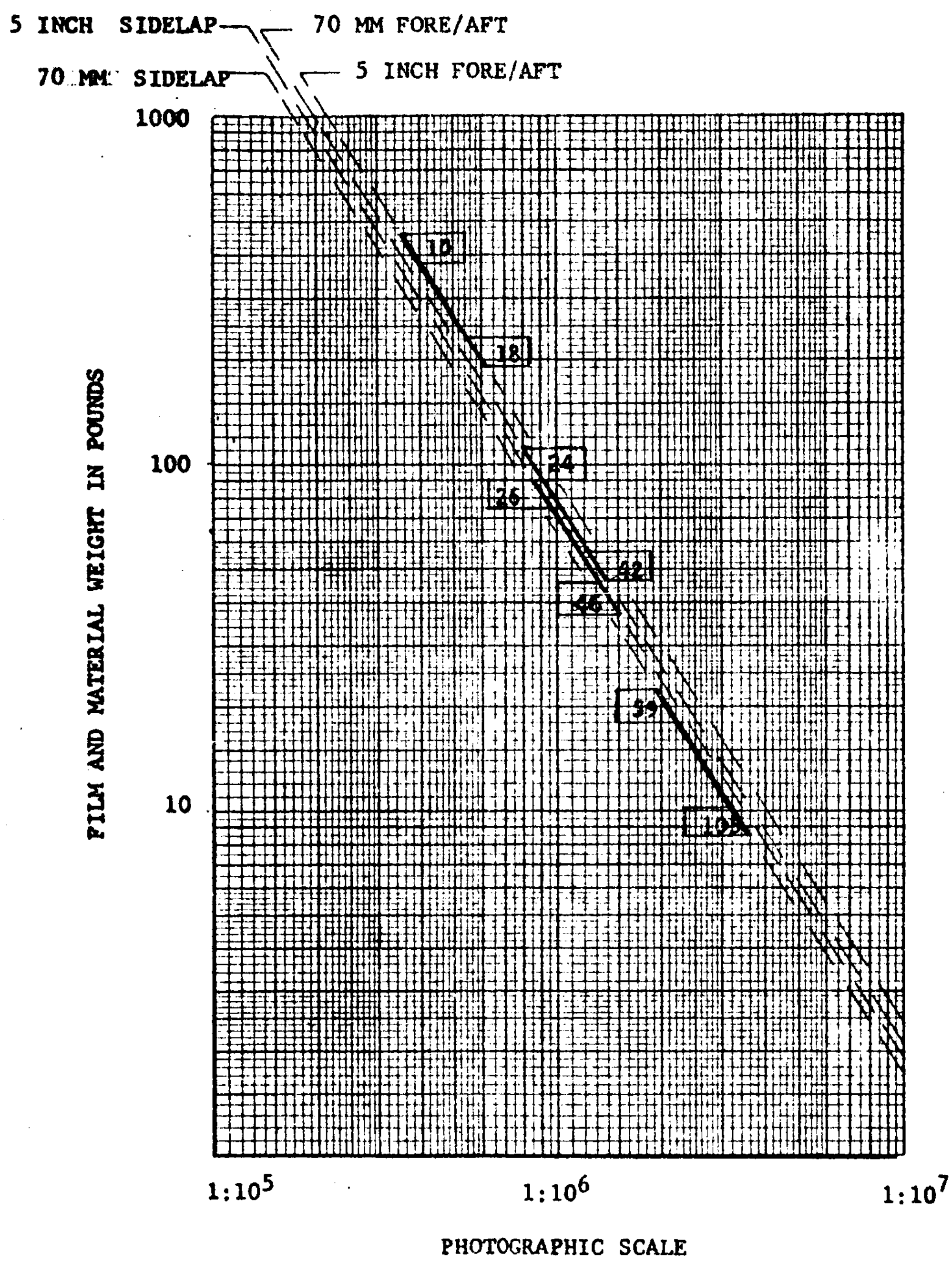
FIGURE 4.27

The choice of 60° and 76° as cut off points was predicated upon the cosines being 0.500 and 0.25 respectively, since swath overlap is a function of cosine latitude (see Figure 4.6).

Weight calculations of material required to map the lunar surface are presented in Figures 4.27and 4.28 incorporate the savings effected by using the $\pm 90°/\pm 60°/\pm 76°$ program. In addition the curves of weight of materials vs. scale of photography incorporate realistic excess film requirements for sprocket holes and data channels.

As previously mentioned, one cannot arbitrarily choose a particular photographic scale at which to operate since the scale is dependent upon other fixed parameters. The limits of permissible scale are darkened on Figure 4.28.

As a contrast to systems that are constrained by film width one can operate at constant scale as does the video unit and require the lens focal length to be such that 10 meters (or any desirable value) be resolved. This will require special film to be cut for the unit.



WEIGHT OF FILM PLUS PROCESS MATERIALS AS A FUNCTION OF PHOTOGRAPHIC SCALE. RESOLUTION IN METERS ENCLOSED. SYSTEM PARAMETERS ALLOW OPERATION IN DARKENED AREAS OF CURVES ONLY.

FIGURE 4.28

The focal length of a lens that always resolves a 10 meter surface element is given as a dashed value on Figure 4.25. The following film format widths are calculated from this focal length and the required ground swaths.

Vehicle Altitude Km	Focal Length (Inches)	Film Size (Inches)
100	11	4.85
200	23	5.95
300	35	7.07
400	47	8.15
500	59	9.25

Ten percent of the film width is allotted to edge sprocket holes and data recording tracks (such as time pulses.) These systems always photograph at a 1:330,000 scale. The weight of film and processing chemicals for this concept will be:

Vehicle Altitude Km	Weight in Pounds	Minification System Weight In Pounds
100	517(+100 Processor)	129(+80 Processor)
300	620(+125 Processor)	155(+90 Processor)
500	680(+150 Processor)	170(+100 Processor)

The required processors would range from 100 to approximately 150 pounds as indicated. The resolution of this system is equivalent to the vidicon/optical fiber sensor unit proposed by this study.

By using an optical fiber coil-to-line technique and a cathode ray tube capable of a spot diameter of 20-30 microns, it is possible to generate a line scan source of sufficient length to allow optical minification. This would enable the film to be read to better resolution than 20μ. Generation of an optical fiber line from 9 to 17 inches long would allow a 2:1 reduction in scanning spot image size* This would result in a 4:1 reduction in weight for photographic material between two systems with the same surface resolution. Film and material weights for minified system are given in the last column of the previous chart. The required length of optical fiber scanning line prior to minification would be:

VEHICLE ALTITUDE (Km)	OPTICAL FIBER LINE SCAN LENGTH (INCHES)
100	8.7
200	10.7
300	12.8
400	14.7
500	16.7

*See Figure 4.29.

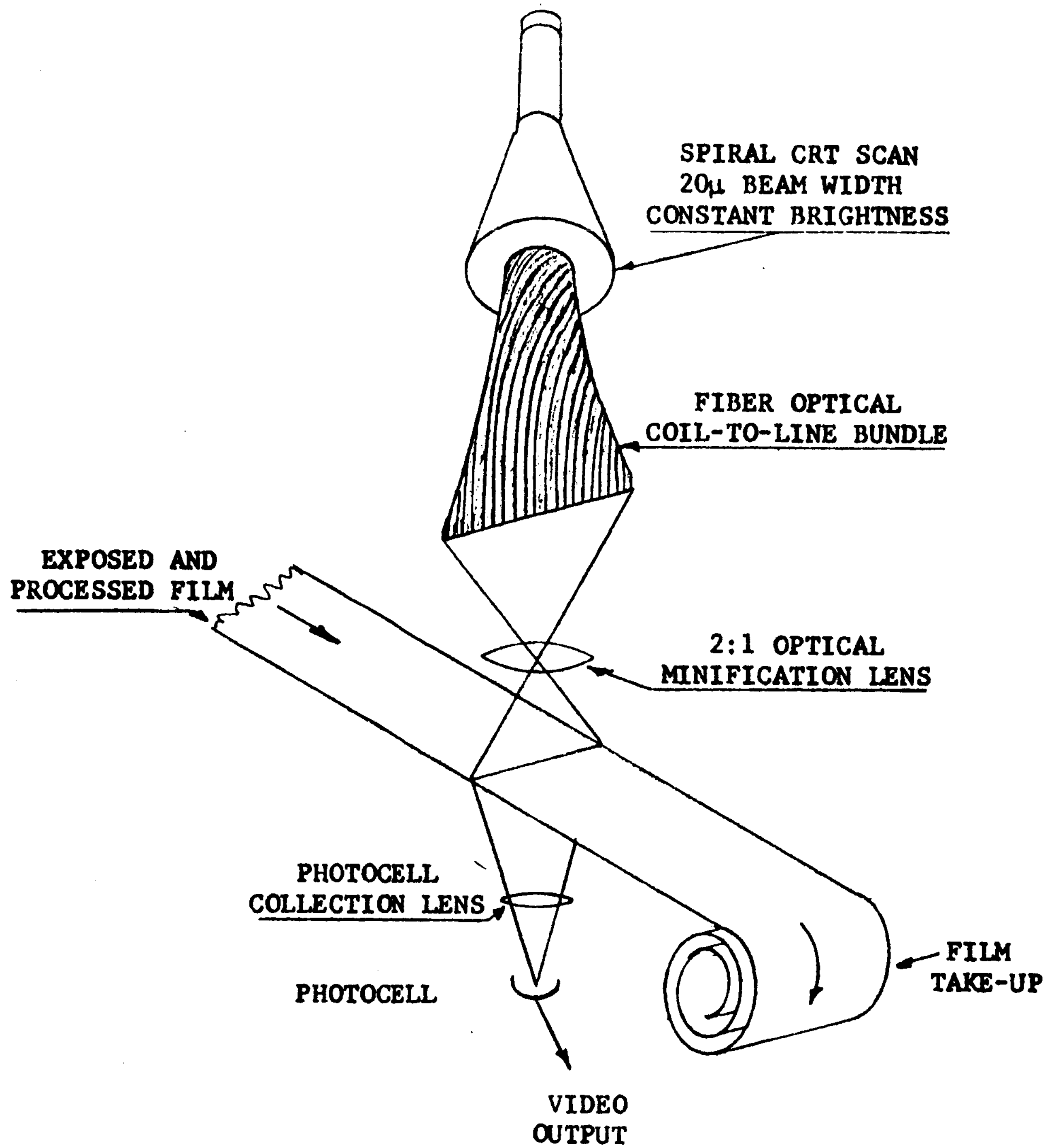


FIGURE 4.29

FIBER OPTICAL/CRT MINIFICATION SCAN TECHNIQUE

These all seem readily attainable with the current state-of-the-art for optical fiber equipment design.

4.5.6 High Acuity Photographic System

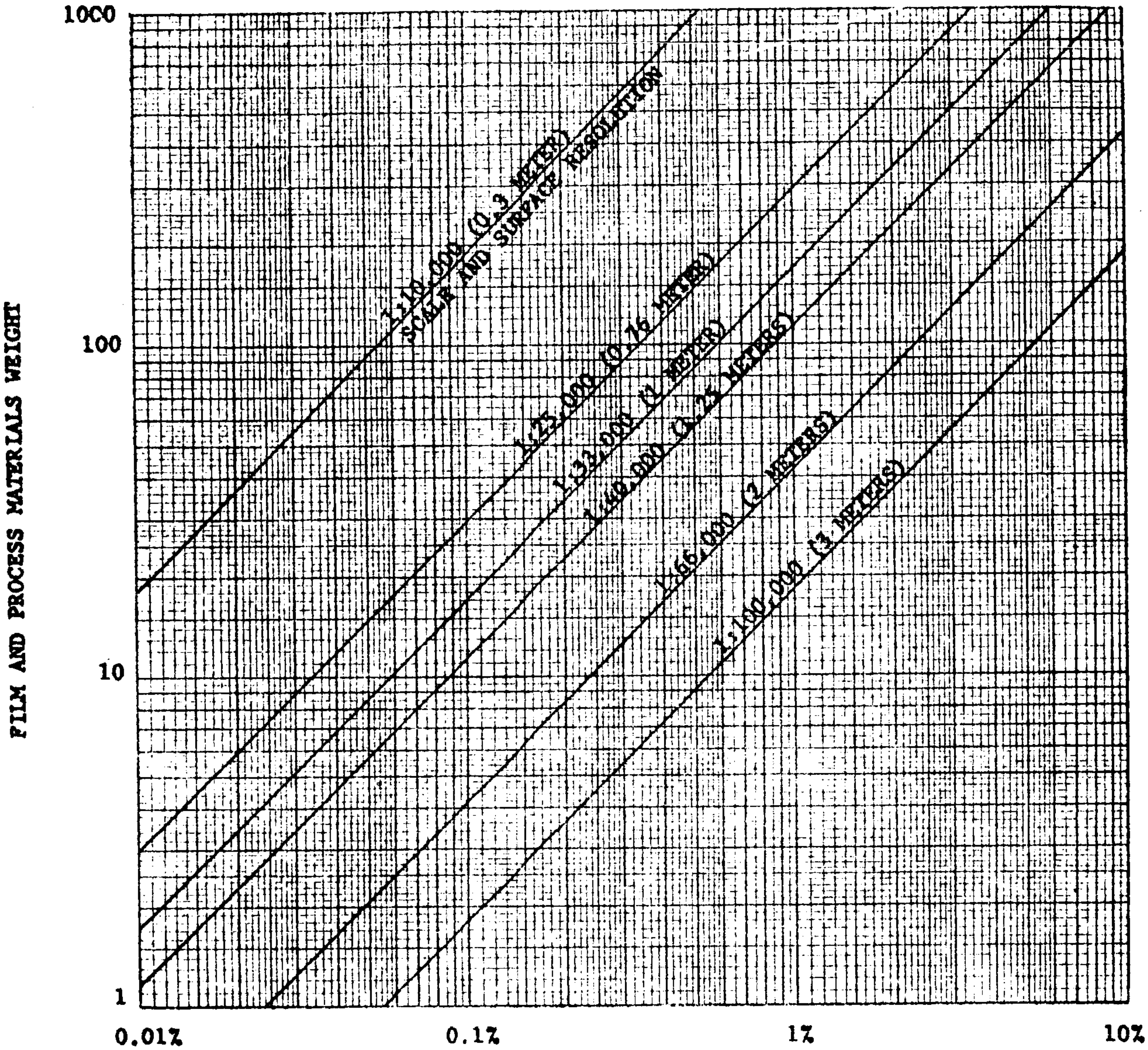
The objective of the high acuity camera is to photograph (or observe) a portion of the lunar surface at resolutions of approximately 1 meter. Since the high acuity camera operation is not constrained by swath width and prescribed overlap it is more advantageous to construct this unit as a fixed scale camera. (i.e. same scale independent of vehicle design altitude.)

The film weight and processing aspects of the high acuity photographic systems are the same as those for cartographic systems discussed. Due to the narrow angle of field of view required (2.5°) a suitable system using 5 inch film format could be constructed. The required camera optics would be heavier because of the necessity for field flattening elements for film use. The focal lengths of the required cameras as a function of vehicle altitude are the same as those shown in the design discussion for the high acuity optical fiber cameras.

Similarly all analyses of pointing error, coverage error etc. discussed in the parametric study are germane to the photographic film high acuity camera problem.

Designing the high acuity camera to have a scale of 1:33,000 allows photography to one meter resolution. The focal length curves described previously illustrate the required focal length as a function of altitude for this constant scale high acuity camera. Figure 4.30 illustrates the weight of film required to photograph different percentages of the lunar surface at various scales. Surface resolution in meters is indicated on the family of curves.

It is possible to apply optical minifaction techniques with an optical fiber line scan just as readily to read-out of high acuity photography as to cartographic camera film. Therefore Figure 4.30 shows additional curves for scales of 1:25,000 and 1:10,000 which would theoretically achieve 0.76 meters and 0.3 meters surface resolution respectively.



PERCENT OF LUNAR SURFACE PHOTOGRAPHED WITH HIGH ACUITY CAMERA. TOTAL LUNAR SURFACE IS 38 X 10^6 KM^2.

FIGURE 4.30

4.5.7 Sterilization in Photographic Systems

Currently three modes of sterilization are available for the film/chemical system. These are heating, irradiation and gassing. It is known that heating and irradiation at the levels required for the VOIS components will destroy the film and/or chemicals.* Similarly manufacture of materials under sterile conditions is not feasible. Therefore gas seems to present the only solution to the problem. It is not known at present what the effect of the sterilization gas will be upon the photographic materials. However it is proposed that the reaction with film/processing materials be studied if desired during the prototype development phase. If the study indicates that gas sterilization cannot be used - and there is reason to suspect this apriori from the chemical characteristics of the Ethylene Oxide, freon, trichlorofloromethane mixture-an alternate procedure would still be possible. This would consist of storing sufficient sterilization gas with the VOIS photographic system on a fail-safe basis. If control of the vehicle were lost and impact

* Aerial reconnaissance film is fogged to a density of 1.0 by approximately 10 Roentgens irradiation.

became probable the whole photographic bay could be thoroughly flooded with gas. This has the disadvantage that the gas will be released on the moon at impact and the gas can be considered a lunar contaminant.

4.5.8 Conculsions of Photographic System Study

The major disadvantages of photographing the moon with conventional film systems are three fold, weight, power requirements and reliability. At least 200 pounds must be allotted for the high and low resolution processors to insure units that are constructed with sufficient integrity to achieve reasonable reliability. These units will require up to 400 watts of power and must be temperature stabilized to 6 8°F $\pm$ 2°F. It requires 300 pounds of film, and chemicals plus 100 pounds of processing equipment to stereoscopically map the moon with a surface resolution of 10 meters. This total of 400 pounds can be compared to the following weight for the equivalent optical film/vidicon unit:*

2 optical fiber/vidicon units at 1 lb each	2.0
2 tape recorders at 70 lb each	140
2 vidicon electronic modules at 15 lb each	30
Total	172 pounds

* The camera weight is neglected in these totals since both systems are essentially the same camera.

In order to obtain a video signal from photographic film, the following series of modules must all operate:

1. Mechanical camera shutter
2. Mechanical film transport (supply and takeup)
3. Film (breakage or tearing possible)
4. Mechanical film processor
5. Film slack box
6. Electro-mechanical film read-out
7. Video read-out circuitry

It is entirely possible that techniques identical to the proposed optical fiber/vidicon sensor will be required for items 6 and 7 above. This series of electro-mechanical operations will be subject to reliability, power consumption and vibration problems.

It is significant to compare the previous series of modules with the optical fiber/vidicon sensor operating chain. This consists of:

1. Vidicon sensor
2. Video circuitry
3. Video tape recorder

As will be discussed later in the section on camera design, the optical fiber/vidicon cameras contain no moving parts and all components are potted (except of course the lens and camera internal space). The film system will have similar or slightly more electronic modules than the optical fiber/vidicon system. The only mechanical portion of the non-film system is the video tape recorder. The relative complexity of the film module series as compared to the non-film module series suggests that significant reliability gain is achieved by the simpler configuration.

5.0 EXEMPLARY SYSTEMS

The section which follows will contain a description of two specific electro-visual, line scan, systems which may comprise the VOIS equipment in the lunar orbiting satellite. Each system will basically consist of (a) a low resolution or cartographic camera, (b) a high resolution camera, (c) a video storage unit, (d) a programmer unit. A block diagram of a typical system is shown in Figure 5.1.

This section will offer two low resolution sub-systems which will respectively map the lunar surface in 10 meter and 30 meter resolution elements. The complete VOIS unit will include one of these low resolution sub-systems and sub-systems (b), (c), and (d) mentioned above. An outline drawing of the complete system is shown in Figure 5.2.

In the specifications which follow, an orbital altitude of 100 KM and field of view of 20.4° are assumed. This field of view subtends distance on the lunar surface greater than the equatorial advance per orbit, in order to account for possible instability in vehicle attitude. This is discussed in Section 4.0. For the specifications that follow, the maximum angular excursions are assumed as:

Roll	$\pm 1°$
Pitch	$\pm 1°$

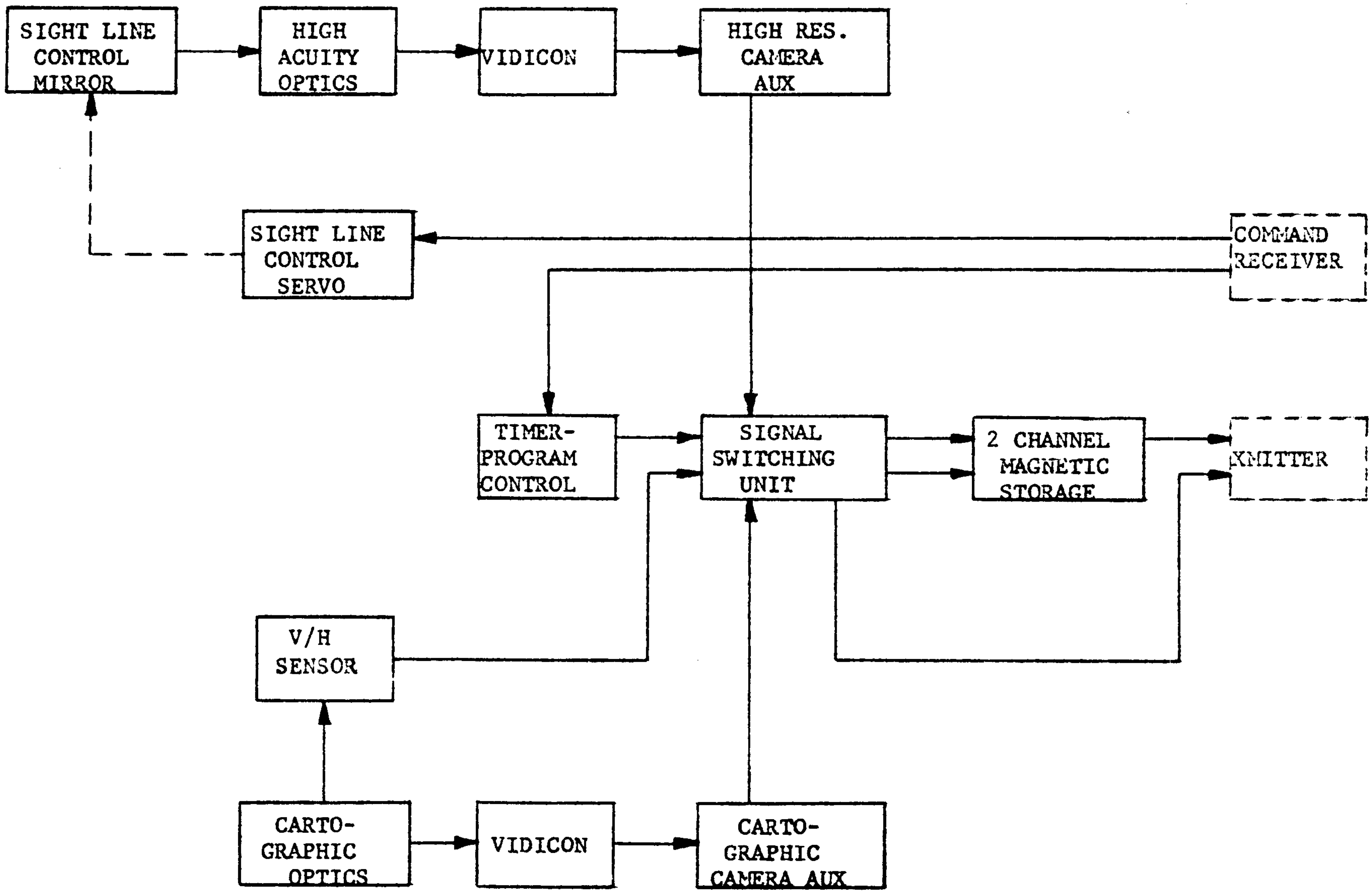


FIGURE 5.1

VISUAL OBSERVATION INSTRUMENTATION SYSTEM

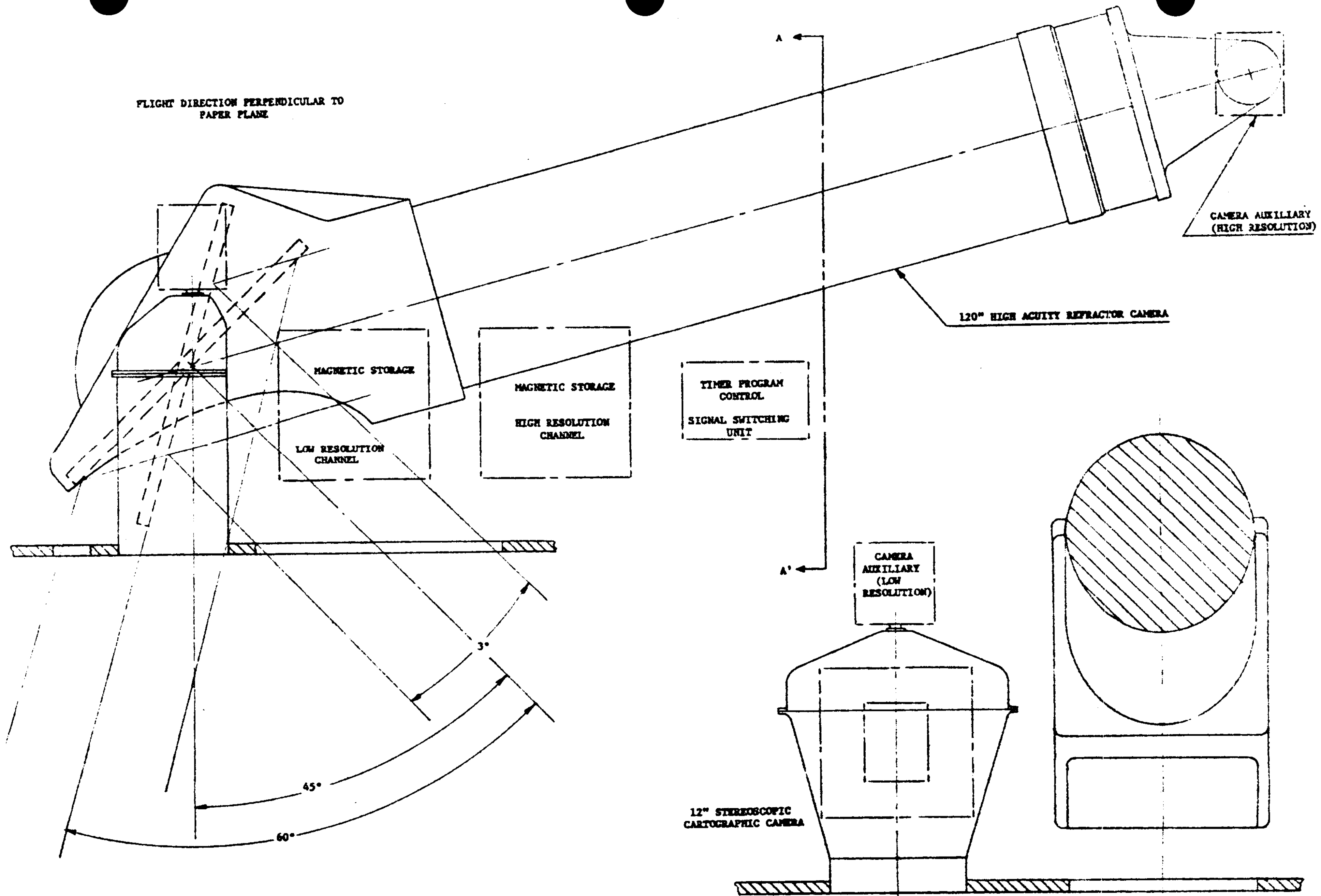


FIGURE 5.2

POSSIBLE VOIS PACKAGING CONFIGURATION

Heading	$\pm 2°$
Altitude	$\pm 5°\%$

The pertinent orbital parameters are as follows:

Altitude	100 KM
Period	118.3 Minutes = 7096 Seconds
Equatorial Advance Per Orbit	32.8 KM
Orbits Per Sidereal Period	332.6
Ground Speed	1537 Meters/Second

The basic relationships and derivations necessary for the calculation of the system parameters which follow are not included in the description of the exemplary systems. All equations and derivations peculiar to these systems are shown in the appendices at the end of the report.

5.1 CARTOGRAPHIC MAPPING SUB-SYSTEM "A"

This sub-system will, within one sidereal period, electro-visually, collect the information necessary for the construction of a topographic map of the entire lunar surface in <u>10 meter</u> resolution elements. The information will be transmitted in real time whenever possible and will utilize the full 1 MC transmission bandwidth. When LOS is nonexistent, and real time transmission is therefore, not possible, the information will be stored until transmission is again possible. All transmission time remaining after low resolution transmission is complete, will be utilized for transmission of high resolution data.

The operation of the camera sub-system will be programmed in such a manner that redundant mapping data will be minimized. This program which is described in detail in Section 3.3, conserves an additional 10% of the sidereal period. This saving, in conjunction with the 25% of the sidereal period by which the LOS exceeds the time required for cartographic mapping, results in a total of 35% of the sidereal period available for high resolution mapping.

5.1.1 <u>Sub-System "A" Specifications</u>

Elemental Resolution	10 meters
Swath Width	40 KM
Angle of View	20.4°
Objective Optics (each linear fiber array)	12 inch, f/4
(V/H Sensor)	12 inch, f/4
Number of Lines (stereo mapping)	2
Ground distance between stereo lines	100 KM

Stereo angle	52°
B/H ratio	1
Number of elements/line	4000
Total number of elements simultaneously viewed	8000
Scan line spacing on lunar surface	7 meters
Scan lines/sec	216
Video bandwidth (real time transmission)	865 KC
Fiber size	.00085 inches
Total number of fibers	11,200
Length of fiber line	9.53 inches
Outside diameter of fiber spiral	0.60 inches
Minimum number of cycles in spiral	6
Maximum area which can be mapped in high resolution	1.18×10^{12} square meters
Weight of Optical System	30 pounds

5.1.2 Cartographic Optical Systems

The design of the recommended triple lens cartographic camera evolved from an analysis of the unique single lens cartographic camera originally proposed for the lunar orbiter program. The major event allowing this shift in concept was the determination that a light weight, well calibrated reconnaissance lens used in conjunction with the fiber optics/vidicon sensor would do an excellent cartographic job.

5.1.2.1 Single Lens Cartographic Optical System

The enclosed Figure 5.3 shows the design of a single lens cartographic camera that obtains stereoscopic surface coverage (fore/aft stereo) on a single pass. The lens illustrated is a current top quality reconnaissance lens having a focal length of 12 inches, an aperture of f4, and weighing 5.73 pounds.

As discussed in the general cartographic section, the most suitable depth sensitivity for the lunar program is obtained when the camera B/H ratio approaches unity. This condition exists when the distance between the fore and aft looking optical fiber lines equals the camera focal length. Expressed in angular terms (See Figure 5.4),

$$\frac{D'B'}{H} = 1 = \frac{DB}{f} \text{ or } D'B' = H \text{ and } DB = f$$

where D'B' is the distance between the surface scanned by the fore and aft looking fiber (or Base B), H is the

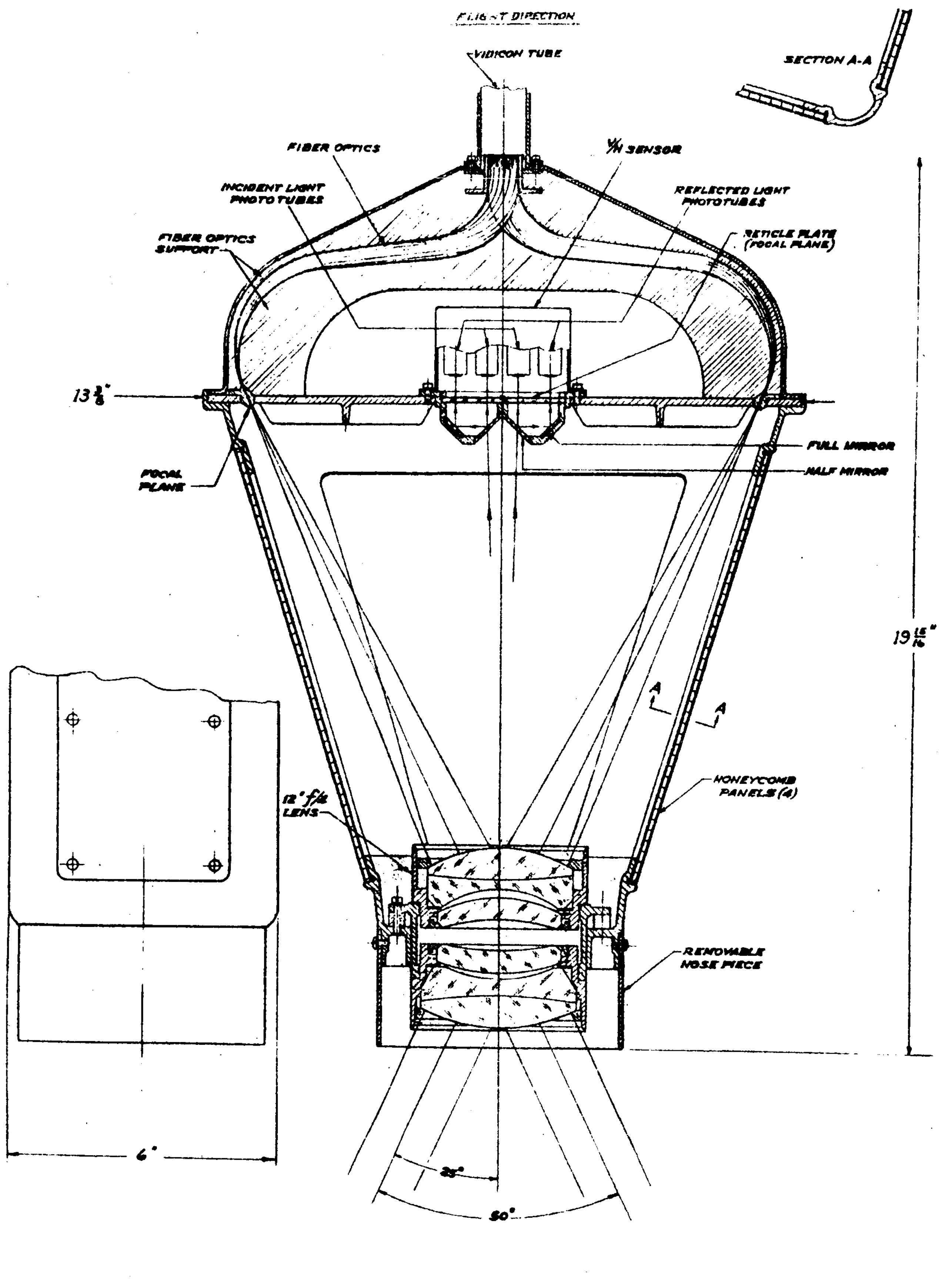
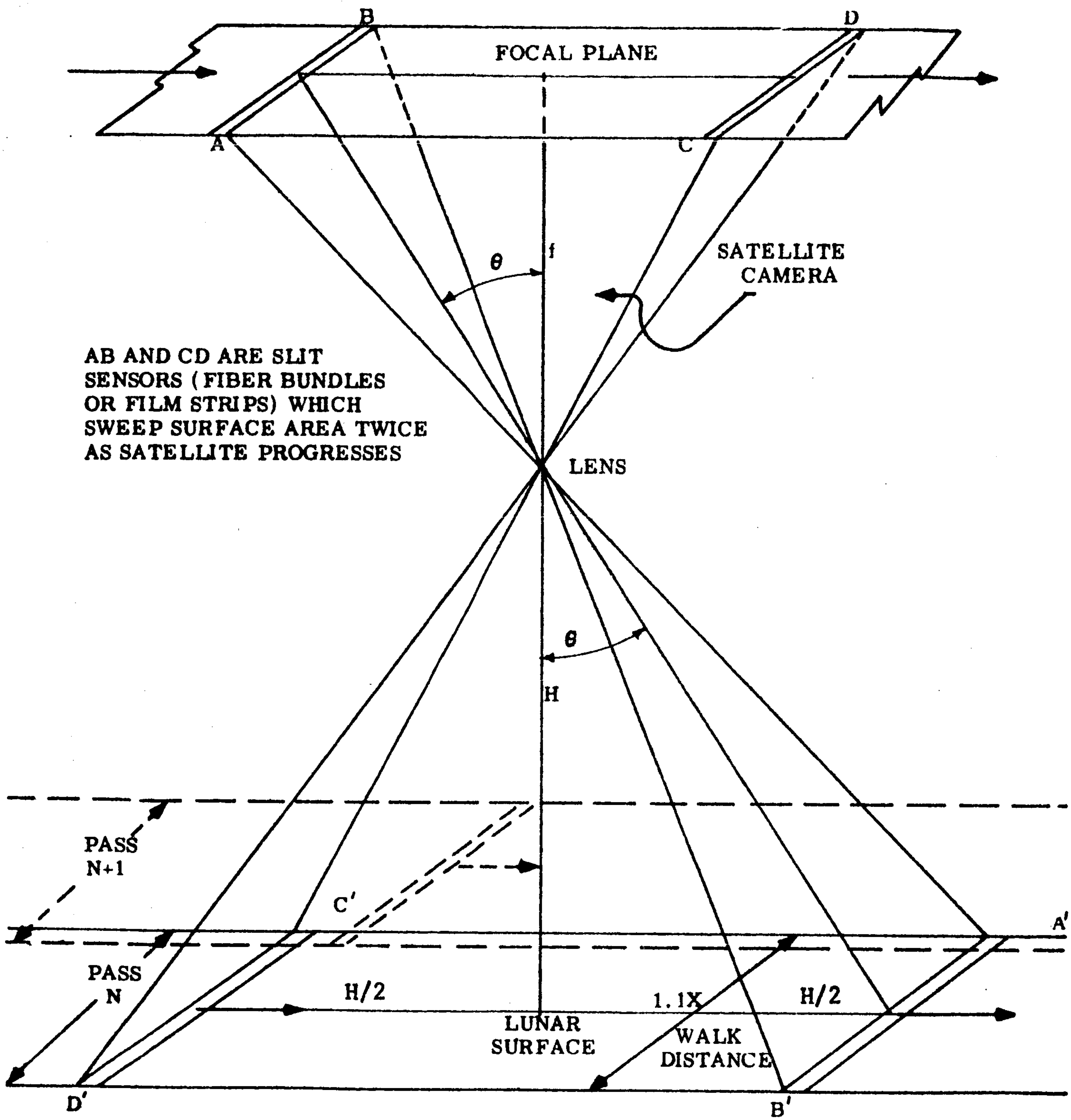


FIGURE 5.3

SINGLE LENS CARTOGRAPHIC CAMERA



FORE/AFT STEREO
CONFIGURATION

FIGURE 5-4

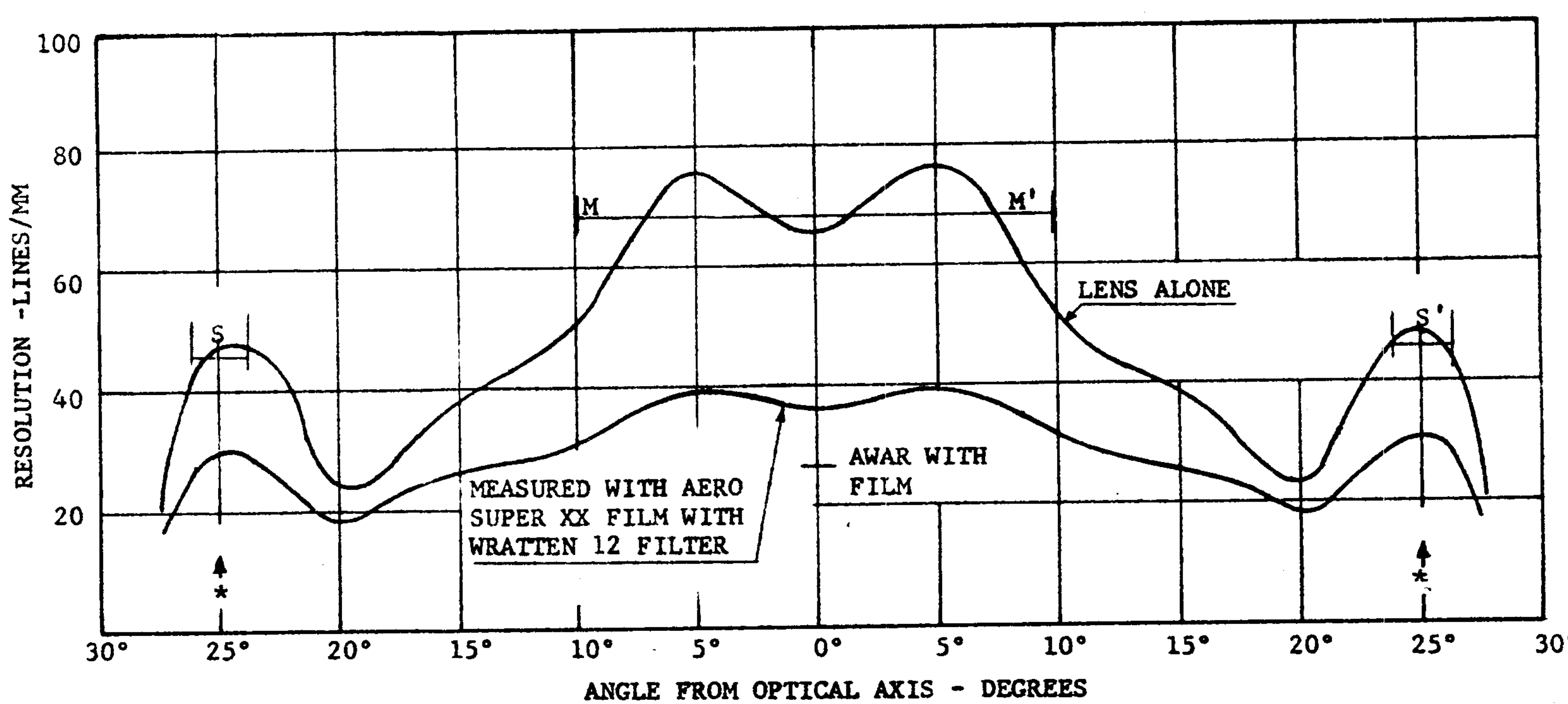
camera altitude, f is the camera focal length and DB is the distance between the fiber line sensors. In terms of the Figure 5.4.

$$\tan \theta = \frac{1/2\ H}{H} = 1/2 \quad \text{or} \quad \theta = 26° \ 34'$$

when B/H ratio is unity.

Figure 5.5 illustrates the resolution of the lens as a function of angular displacement from the optical axis. Part of the reason for the choice of the particular lens is the peaking up of lens resolution between 23.5° and 26.5°. The optical fiber lines can be so placed that they fall within the peaked resolution zone about 25°. The angular width of the annular ring containing the optical fiber line sensor line will be approximately 3°. This annular resolution zone for the line sensor is indicated in Figure 5.5 by segments S and S'. The B/H ratio obtained by centering the fiber line sensors about 25° instead of the desired 26° 34' will be 0.94. This will change the vertical sensitivity from 10 meters (B/H = 1) to 11 meters (B/H ~ 0.94), a negligible effect.

Since the two optical fiber line sensors (plus redundant fiber lines incorporated for vidicon reliability) utilize



* FIBER BUNDLES AT 25° PEAK IN SINGLE LENS CAMERA

FIGURE 5-5

RESOLUTION OF 12 INCH f/4 LENS

so little of the area of the focal plane, there is adequate space for incorporation of other instrumentation within the camera. One such item is the V/H sensor shown which detects yaw misalignment of the camera plus the ratio of ground velocity to altitude. This unit is described in detail in Appendix A.

Preliminary calculations indicate this camera will weigh 16 pounds (7.27 kilograms) plus approximately one pound for each additional vidicon/optical fiber sensor pair incorporated for reliability redundancy.

A significant feature noticeable in Figure 5.3 showing this camera is the absence of a shutter or adjustable aperture. In fact the camera contains no moving parts, and all components, the fibers, V/H sensor and vidicon tube are potted. Normal film cameras require shutters and adjustable apertures to control exposure. Within the lunar orbiter cameras all corrections in "exposure" due to lighting differences upon the moon are effected electronically within the vidicon circuitry. This enables the lens to be operated at the fixed aperture which results in best resolution. The reliability advantage due to having a camera with no moving parts is obvious especially when considering the time of operation and environment requirements of the lunar orbiter.

The major disadvantage to this single lens configuration is the fall off of light intensity as one approaches the edge of the field of view. The axial transmission of this type of lens is in excess of 80%. However, the intensity at approximately 29° off the optical axis will be down to 25% to 29%. In addition to the lighting problem, better resolution is obtained by using the lens on its optical axis. Since there is significant variation in resolution between lenses of the same design, more detailed testing would be required to obtain a lens with adequately shaped 25° resolution side lobe peaks. Use of the lens on axis results in an easier quality control problem during fabrication phases.

5.1.2.2 Multiple Lens Cartographic Camera

The enclosed Figure 5.6 illustrates a multiple lens cartographic camera that is an outgrowth of the single lens unit shown in Figure 5.3 . As previously mentioned,

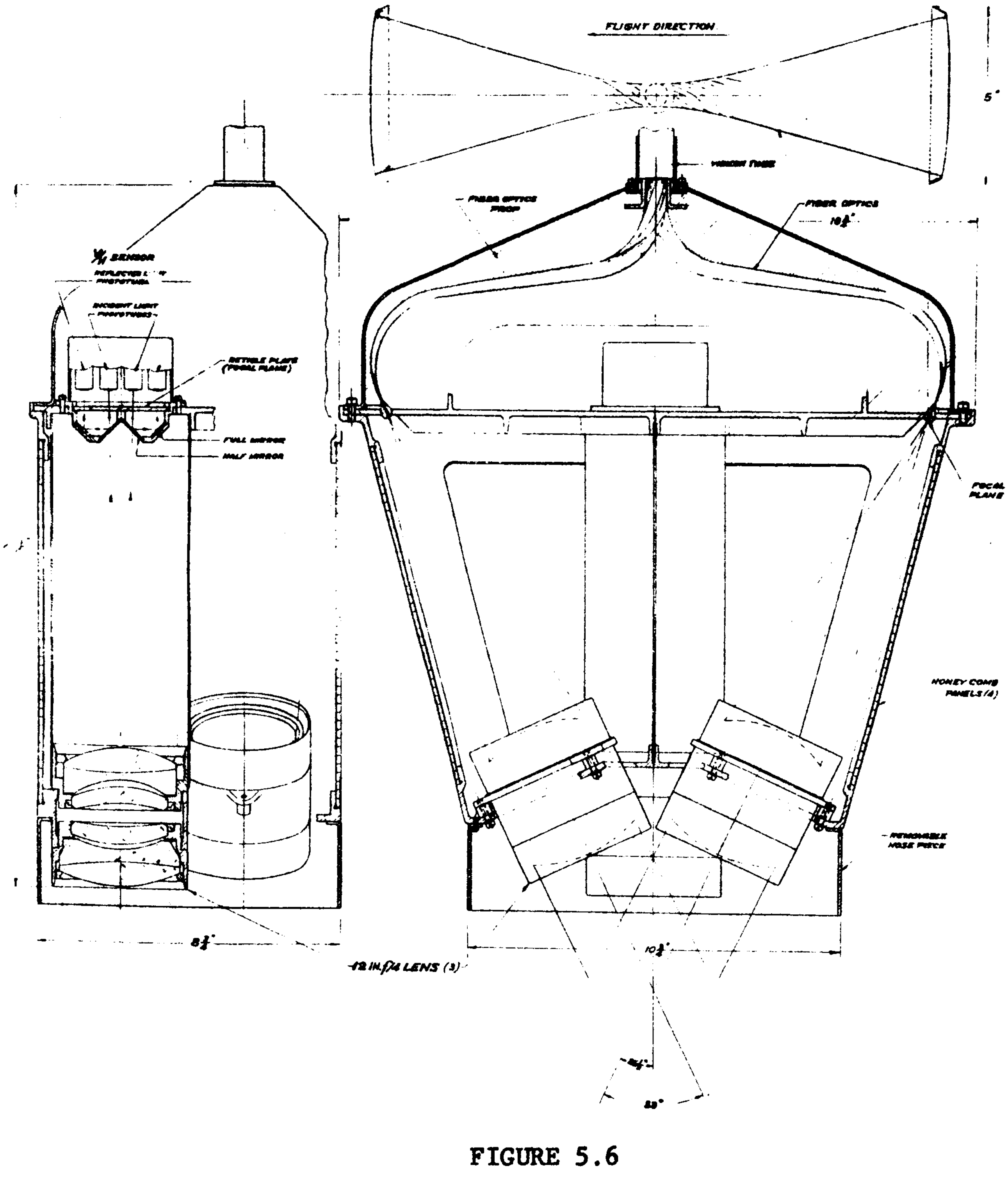


FIGURE 5.6

MULTIPLE LENS CARTOGRAPHIC CAMERA

the availability of suitable 12 inch f4 lens weighing less than 6 pounds each makes it quite feasible to consider multi-lens cameras.

The significant difference with the camera in Figure 5.6 is that each optical fiber line sensor has its own lens. The optical fiber line is centered on the lens optical axis, thus operating in a region of better resolution and significantly greater light intensity. The angle subtended by the optical fiber line is approximately $\pm$ 10°. On Figure 5.5 the line M M' illustrates the extent of this angle as expressed on the lens resolution diagram.

In the configuration illustrated, three lenses are used, one for each of the fore and aft optical fiber line sensors plus a lens with its optical axis vertical for the V/H and yaw sensor.

Again as with the single lens camera, the triple lens unit contains no moving parts. The placement of redundant optical fiber lines sensors for reliability considerations is lens critical than in the off-axis case because the zone of acceptable resolution is much larger.

Weight of this camera will be approximately 30 pounds (13.6 kilograms) plus one pound for each additional redundant optical fiber line/vidicon system incorporated.

5.1.2.3 Fiber Optics

Figure 5.7 illustrates an arrangement of optical fibers which, when coupled with appropriate objective optics, will provide the double coverage required for stereoscopic mapping. The placement of the two linear fiber arrays as shown will accomplish the "fore/aft" stereo configuration discussed in Appendix D. As can be observed from the drawing, the ends of both arrays are bent back toward the optical axis so that they are parallel to the line of sight of each array. This is done in order that the light rays emanating from the objective enter the fibers parallel to the axis of each optical fiber.

As a result of the fact that the line of sight of each fiber line is inclined to the spherical lunar surface, a perfectly straight line of fibers subtends a strip of surface which is not a great circle. In order to

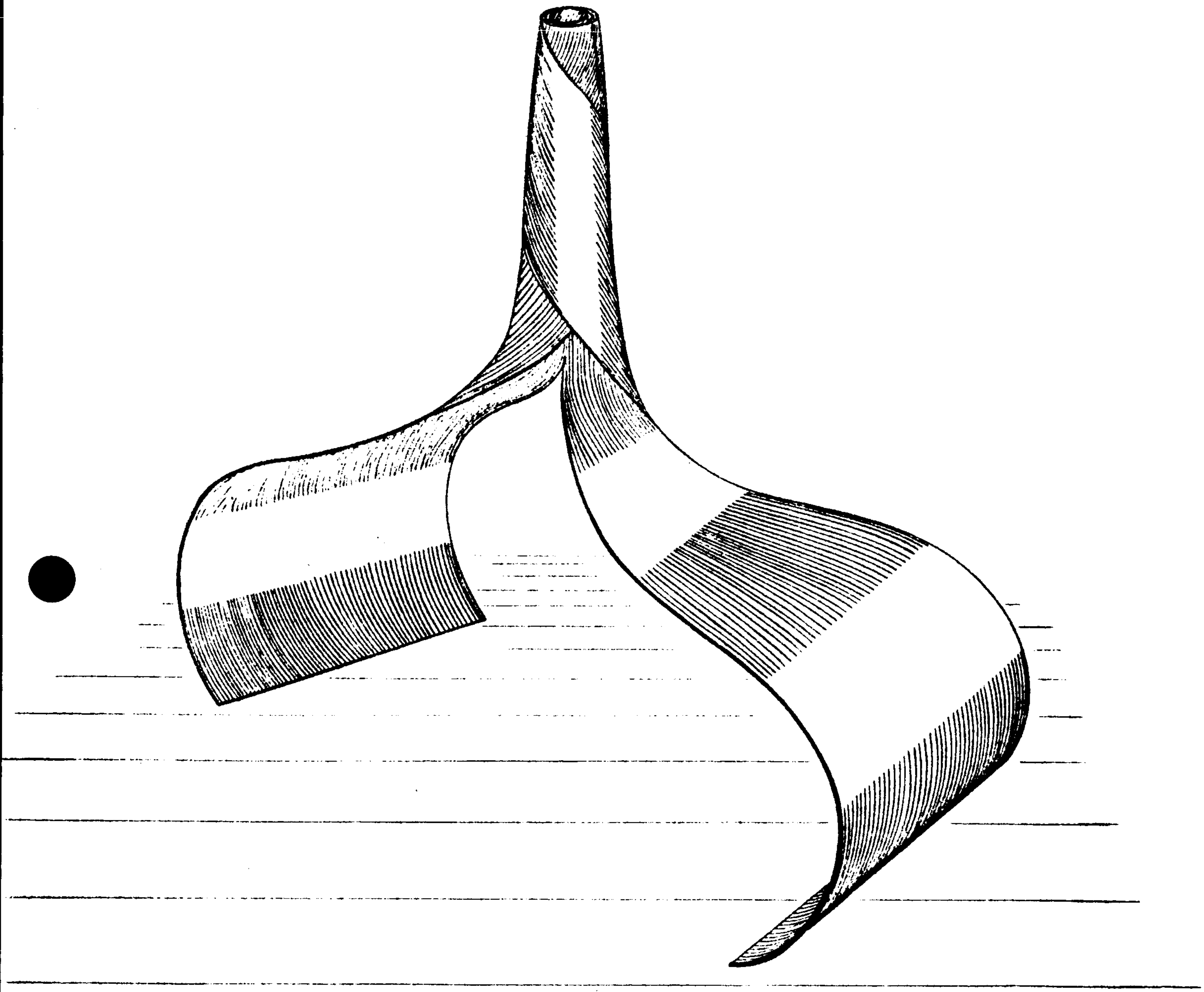


FIGURE 5.7

FIBER OPTICS

eliminate the photogrammetric complications arising from such a situation, it was suggested, in an earlier report, that each fiber array be curved to exactly compensate for this error. However, the accuracy of compensation is a sensitive function of altitude and the photogrammetric problems associated with the incorrect compensation are more severe than the uncompensated case. Therefore, it is felt that the fiber array should remain linear.

The fibers at the photosensor end of the system could be arranged in a number of configurations for the purpose of distributing the linear array over the area of the photosensor. For example, the scan lines can be broken into a number of segments and arranged in the form of a raster at the photosurface. A circular configuration is also possible.

The rectangular geometry of the raster with respect to the cylindrical symmetry of the pickup tube, makes difficult the optimization of focus and flatness of field. When the image is reconstructed into line form, these discrepancies will appear as a number of parallel bands along the length of the strip.

In the case of a circular arrangement, the length of fiber line determines the diameter of the fiber circle at the photosensor. Since the diameter of the sensitive area on the pickup tube is a relatively inflexible parameter, optical reduction through a relay lensis dictated. This necessitates the use of a sensor with increased sensitivity as a result of losses in optics. The state of the art in electronic readout systems does not possess sufficient margin to permit this arrangement.

The spiral fiber array, in which the linear configuration is curled into a multi-layer spiral, is limited only by the area of the photosensitive surface. The spiral, as well as the circular array, takes advantage of the circular symmetry of the photosensor.

If we assume, by the Kell factor, that 1.4 fibers are required for each 10 meter resolvable element, and examine the condition at an altitude of 100 KM, we observe that,

the total number of elements simultaneously viewed = 8000 and

the total number of fibers= 11,200.

Discussions with representatives of the American Optical Corporation and Bausch and Lomb Corporation have yielded the fact that a practical diameter for individual optical fibers is 21 microns or .00085 inches. Therefore, the length of each fiber line is equal to

$$11,200 \times .00085 = 9.53 \text{ inches}$$

Assuming that the fiber line is to be wrapped into a spiral which is compatible with the photosensitive area of a one inch vidicon, the 9.53 inch fiber line must be converted to a spiral with an outside diameter no greater than 0.6 inches. The circumference of the outer turn of the spiral is, therefore, 1.885 inches in length. In order to encompass one fiber line, a minimum of six turns in the spiral is required. Since each fiber line is one fiber thick and we provide a .010 inch separation between layers, the total thickness of the spiral is equal to

$$6 \times (.00085 + .010) = .06510 \text{ inches.}$$

5.1.3 Photosensor

For line scan systems of the type described in this report, the most practical photosensor appears to be a modified electrostatic vidicon with a fiber optics face-plate. The vidicon offers a number of advantages in applications of this type, in the fact that its physical and electrical parameters are extremely compatible with the requirements of airborne or spaceborne systems and are a considerable improvement over those of other applicable sensors such as the image orthicon.

All-electrostatic, ruggedized vidicons are presently available, which offer the additional advantage of complete elimination of the magnetic components required for focus and deflection. This effects a considerable saving in space, weight, and power consumption.

From Appendix B, the number of photons per unit area per second entering a given aperture is equal to

$$n = \frac{4N\cos\theta}{\pi^2 R^2}$$

where, N is the total number of photons leaving an element on the lunar surface,

R is the distance in meters

θ is the angle off the normal to the surface.

If the average brightness is assumed to be 910 foot lamberts, 9.8×10^5 lumens are emitted from a surface element 10 meters square. Since one lumen is equal to 10^{16} photons, 9.8×10^{21} photons (N) per second leave the elemental surface area. Thus, at an altitude of 100 KM directly above the emitting surface (θ=0),

$$n = \frac{4 \times 9.8 \times 10^{21} \text{ Cos } 0°}{\pi^2 \ (10^5)^2}$$

$$= 3.98 \times 10^{11} \text{ photons per second per square meter}$$

Since the optical aperture is 4.56×10^{-3} square meters, and the integration time is $\frac{1}{216}$ seconds, 84×10^5 photons per second enter the aperture.

A conversion efficiency of one electron for 10 photons represents the state of the art, therefore, 84×10^4 electrons will be available to indicate the relative brightness of a given element. The signal-to-noise ratio at the system input is equal to the square root of this number so that the primary S/N is considerably better than that which can be attained in succeeding links of the system.

Unfortunately, the photoconductive surface presently found in most vidicons was designed to be compatible with conventional television scan rates. As a result, the lag associated with the surface, is appreciable, and image persistence, after 0.5 seconds, as great as 40%, can be observed.

The high resolution line scan system described herein requires scanning of a given element of the photoconductive surface 216 times per second and the persistence characteristic described above would make the device unuseable.

Discussion with a prominent manufacturer of vidicons (General Electrodynamics Corporation) has yielded the information that development of a fast response surface seems quite feasible. In fact, surfaces demonstrating extremely low persistences have been discovered as by-products of other experiments.

GEC has suggested that a practical approach to the problem would be to utilize a return beam, electron multiplier, vidicon, in conjunction with the new surface. A vidicon of this type, but without the short time constant surface, has been developed and is currently available.

Because of the short frame time of the present system, a low resistance photoconductive target can be used, thus reducing the time constant. However, due to this low resistance, the resulting video signal would be significantly reduced. Through the use of a return beam vidicon, it is feasible to incorporate an electron multiplier in the tube, thus recouping this loss and producing an adequate output signal.

In order to maintain registration of the scanning beam with the spiral array of fibers, a special metallic pattern must be provided on the photosurface of the vidicon. This pattern will consist of metallic borders on each side of the spiral as is shown in the sketch of Figure 5.8 . When the electron beam impinges heavily upon these surfaces, an error voltage will be generated which will be applied to the deflection generator. In the deflection generator, the deflection waveform will be modified to correct the radial position of the beam. The instrumentation of this system will be discussed in Section 5.1.4.3.

In order to alleviate problems associated with mechanical registration of the fiber bundle with respect

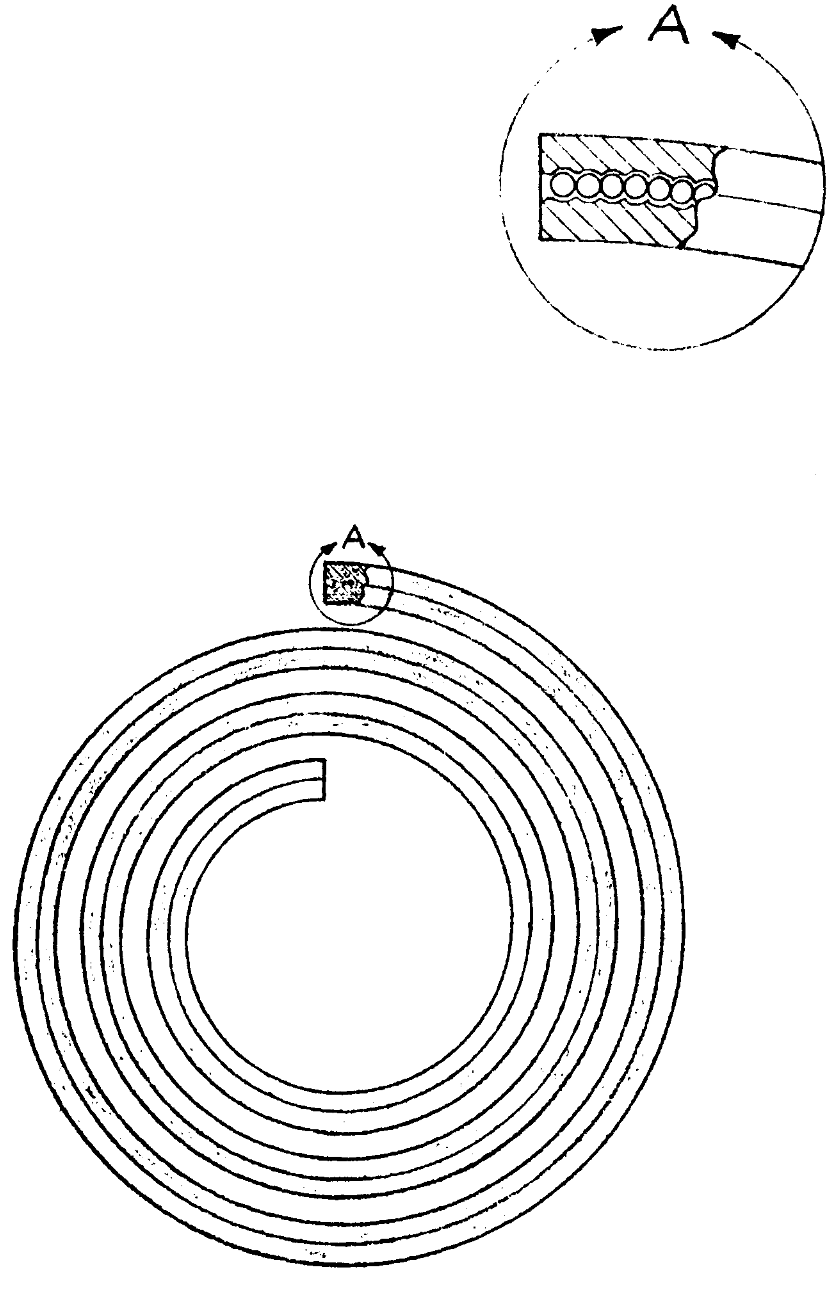


FIGURE 5.8

TYPICAL REGISTRATION SENSOR PATTERN

to the vidicon, the possibility of obtaining vidicons and fiber arrays as integral units should be investigated.

In general, the development of a new vidicon with the above characteristics does not seem to be a serious problem, and such a development will provide a photosensor which is ideal for the present problem.

5.1.4 Camera Auxiliary

The Camera Auxiliary unit contains all the electronic circuitry necessary to convert the image on the photosurface of the vidicon into a composite video signal at the input terminals of the signal switching unit. The Camera Auxiliary consists of four basic units, as follows:

a) Preamp and Video Processor

b) Timer-Sync Generator

c) Deflection Generator

d) Power Supply

A block diagram of the Camera Auxiliary is shown in Figure 5.9.

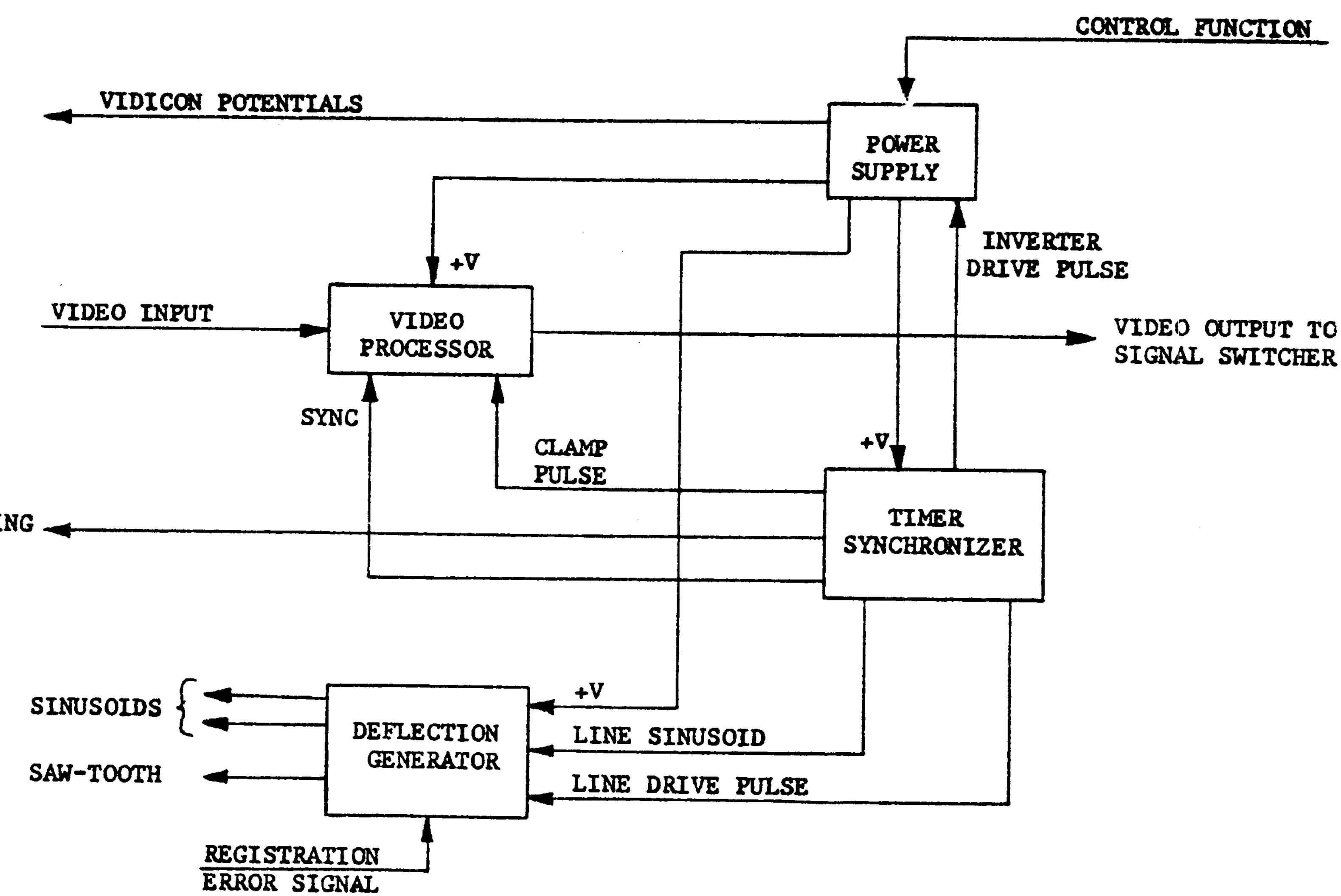


FIGURE 5.9

CAMERA AUXILIARY

5.1.4.1 Preamplifier and Video Processor

The preamplifier must accept the extremely low level video signal emanating from the vidicon and amplify it to a level compatible with the input of the video processor. In the design of video preamps, for applications of this type, careful consideration must be given to the noise level of the first amplification stage. In fact, in most video amplification systems the overall S/N is primarily determined by the noise level in the preamp.

Choice of a low-noise silicon, transistor such as the Fairchild 2N1613, and operation at relatively low collector voltages are of prime importance for operation at minimum noise levels. Since the bandwidth of the 10 meter subsystem is less than 1 megacycle, video S/N ratios of 38 db are attainable.

The video processor must;

a) Amplify the signal from the preamp to a convenient level for processing.

b) Recoup the high frequency level lost due to shunt capacity at the preamp input.

c) Restore the dc level by clamping.

d) Insert the synchronizing waveform into the video signal.

e) Provide sufficient level of composite video signal across an impedance compatible with the input of the succeeding unit.

A block diagram of the video processor is shown in Figure 5.10.

The high and low frequency response figures for the 10 meter system are 865 KC and 7.3 CPS respectively. Bandwidths of this order are easily attainable. The low frequency response is calculated, taking into account the improvement realizable through DC restoration at the end of each line. This restoration is provided by the line clamp circuitry which returns the video signal to a fixed level at the end of each line.

5.1.4.2 Timer-Sync Generator

The Timer-Sync Generator supplies the basic timing information for the entire camera system. This unit provides the sinusoid for the deflection spiral, the

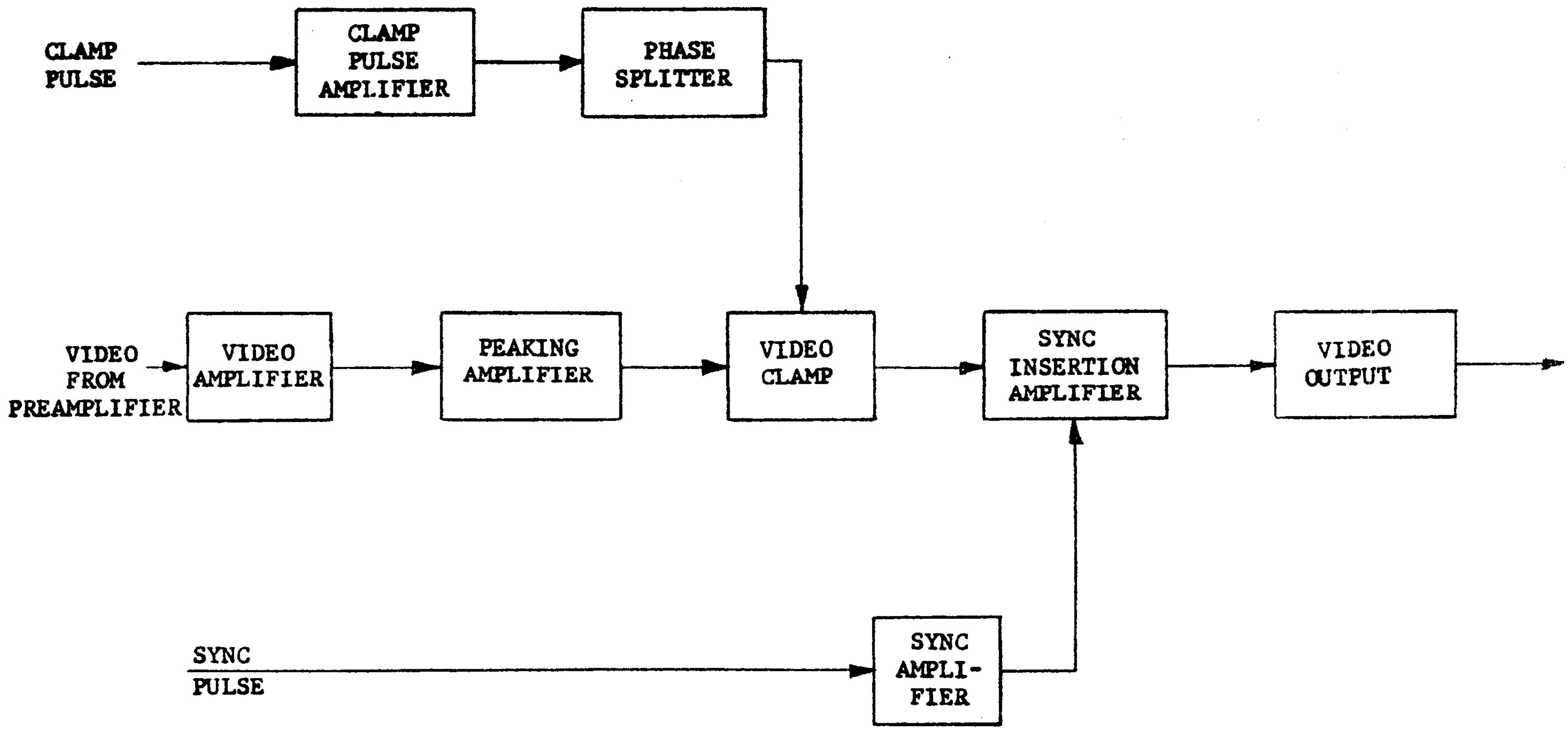


FIGURE 5.10

VIDEO PROCESSOR

drive pulse for the deflection sawtooth waveform, the sync pulse, and various synchronous pulses for clamping, blanking and power supply synchronization. A block diagram is shown in Figure 5.11.

The master frequency for the 10 meter system is derived from a 1296 cps sinusoid oscillator, the output of which is used for generating the deflection spiral. The 1296 cps, through 6:1 frequency division generates the basic line rate pulse (216 pps) which triggers the various waveform generators. A rectangular pulse at line rate is applied to the cathode of the vidicon in order to reduce the beam to zero during retrace. Units of this type have been designed and developed and no difficulty is anticipated.

5.1.4.3 Deflection Generator

The Deflection Generator must provide the waveforms, which, when applied to the deflection plates of the vidicon, will deflect the electron beam in a spiral path corresponding to the ends of the fiber optics.

A block diagram of the deflection generator is shown in Figure 5.12. The 1296 cps sinusoid from the Timer-

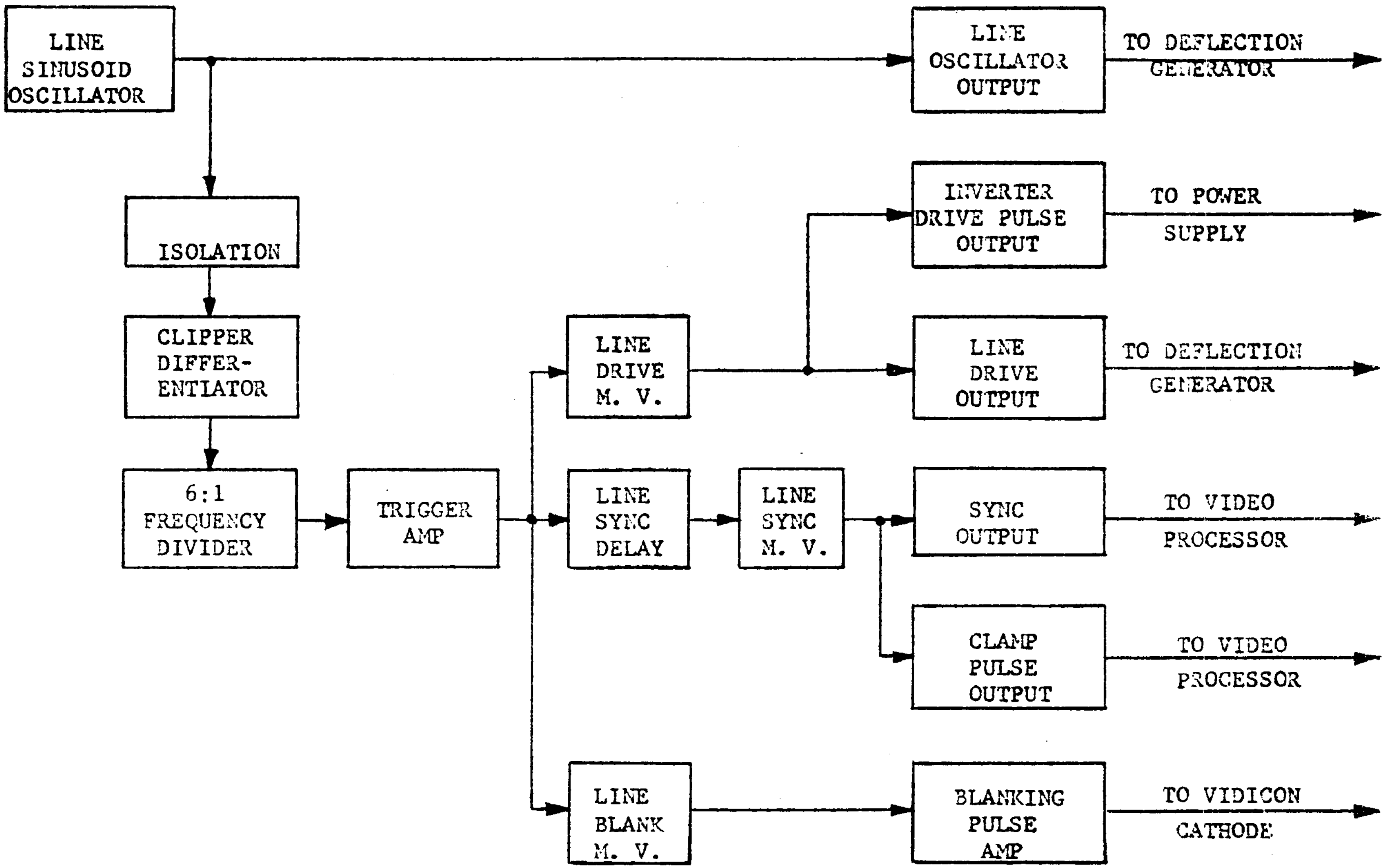


FIGURE 5.11

TIMER-SYNC GENERATOR

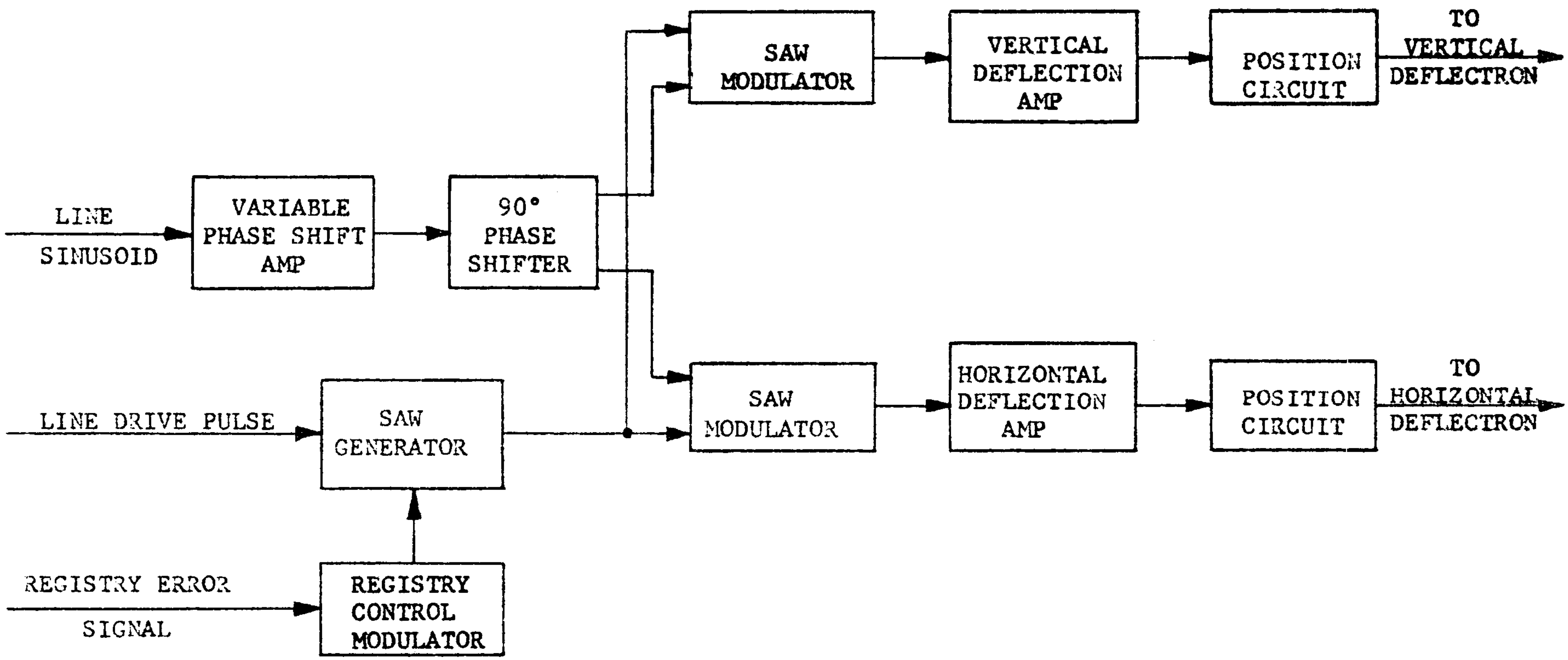


FIGURE 5.12

DEFLECTION GENERATOR

Sync Generator is introduced into a variable phase shift amplifier which permits adjustment of the relative phase of the sinusoid with respect to the sawtooth, thereby determining the angular position of the start of the spiral. The sinusoid is then split into two equal signals differing in phase by 90°. Each signal is amplitude modulated by a sawtooth waveform repeating at the 216 cps line rate. The resultant waveforms are amplified and introduced into the vidicon deflection system.

Registration of the electronic spiral with that comprised by the ends of the fibers is accomplished through a feedback system. When the electron beam departs from the spiral path, it impinges upon the metallic strips bordering the spiral. A description of these metallic registry correction strips is given in Section 5.1.3. The signal thus generated is unbalanced in the direction of the departure. This signal is differenced and the resultant error signal drives a registry control modulator which modulates the amplitude of the sawtooth. Since the instantaneous amplitude of the sawtooth always determines the radial position of the beam, modulation of this amplitude serves to drive the beam radially back into the spiral path.

In order to lighten the burden upon the registry correction loop, sawtooth amplitude and linearity; sinusoid amplitude, phase shift and distortion; and positioning voltage regulation must be carefully controlled. In general, the circuit design will be highly degenerative in nature.

5.1.4.4 Power Supply

A separate power supply is provided for each subsystem.

The power supply is of the standard, regulator-synchronous inverter type. A block diagram is shown in Figure 5.13 Primary DC power, on the order of 25 watts at approximately 30 volts, is introduced into a regulator which provides a well regulated supply voltage to a power oscillator. The power oscillator is of the saturating core type. The alternating waveform thus generated is amplified by step up windings on the inverter transformer. All supply voltages to the various modules and the vidicon are derived from these windings. Additional regulation is provided for the voltages supplied to the

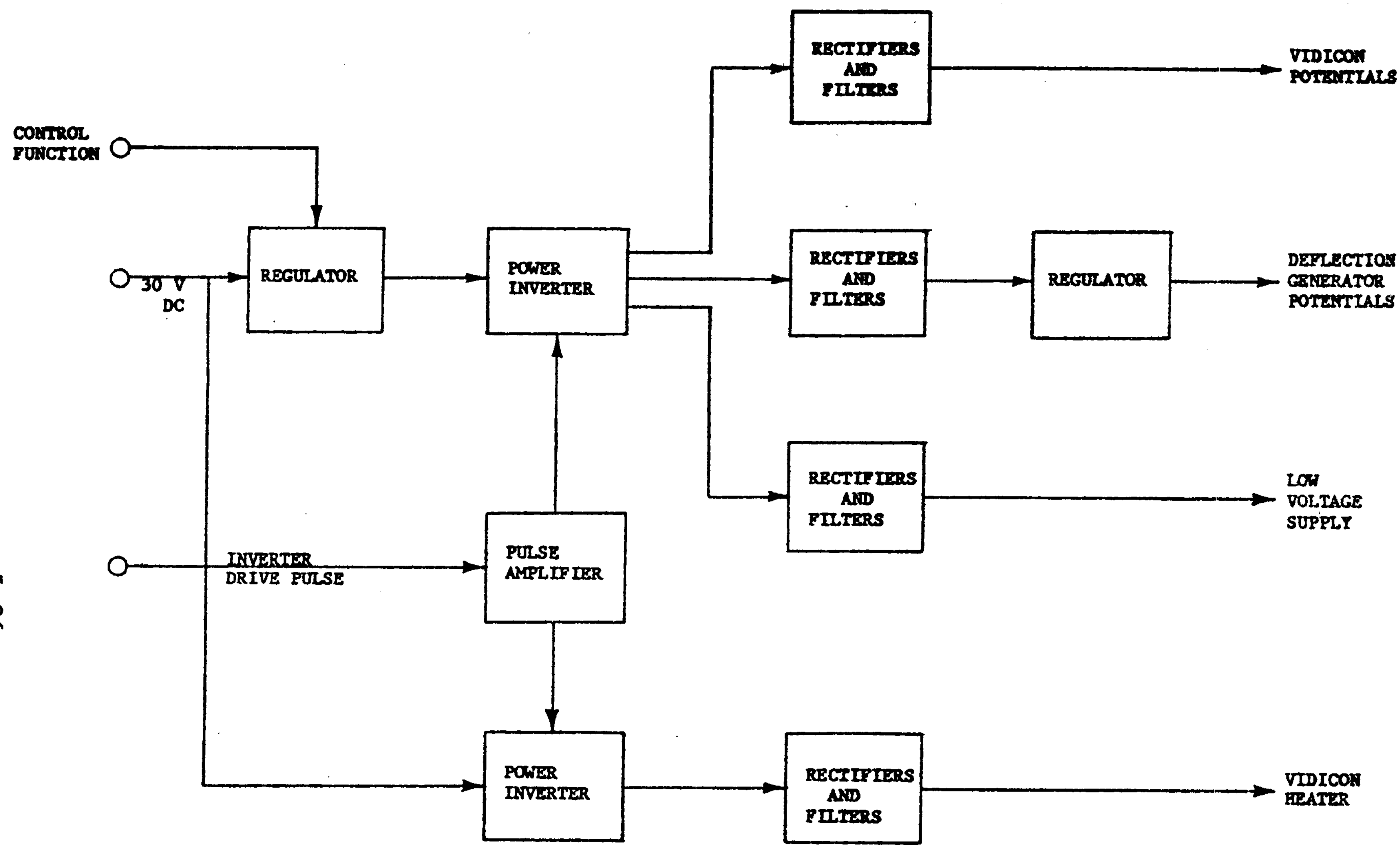


FIGURE 5.13

POWER SUPPLY

deflection generator.

The power inverter operates in synchronism with the line rate of the camera system through the introduction of a line drive pulse which initiates the transition between states of the oscillator. This synchronous operation minimizes the effect of power supply ripple in the final presentation since ripple modulation does not move with respect to the scan.

A separate power inverter supplies the heater voltage for the vidicon in order to permit continuous operation of the vidicon heater during the entire lunar experiment. From a reliability standpoint, it is not desirable to energize and de-energize the heater coincident with the camera program.

The camera control function will be applied to the regulator which de-energizes all circuits with the exception of the heater.

5.1.5 Video Storage

As was discussed in the Status Report of November 1960, the VOIS equipment must include facility for storage of the video information gathered by the electro-visual system.

A low resolution map of the entire lunar surface cannot be accomplished in "real time" since LOS does not always exist during the period in which mapping is possible. Therefore, information must be stored until LOS is re-established and the information read out at that time.

Mapping portions of the lunar surface in 1 meter resolution elements necessitates an information rate of 4.32 MC which cannot be transmitted because of transmission bandwidth limitations. The high resolution information, therefore, must be recorded in its entirety and read out at a lower rate compatible with the bandwidth.

The high resolution (1 meter) mapping will be performed in selected areas based upon examination of the low resolution information received on previous orbital passes. Since the time available for high resolution mapping is limited, and since it is possible to successfully effect high resolution mapping in an area two orbits away from the current position of the satellite, it is important that all information be read out before the succeeding pass. Therefore, the high resolution recording system may be expected to record and reproduce information on each orbit, which dictates approximately 330 record-readout cycles during the first month of the lunar orbiter experiment.

Since storage of low resolution data is required only when LOS is nonexistent, and since it is necessary to transmit all stored information before the succeeding orbit, approximately 100 record-reproduce cycles will be required of the low resolution recording system.

The quantity of high resolution mapping which may be accomplished is dependent upon the transmission time available after all low resolution information, in a given orbit, has been transmitted. In the vicinity of the first and third quarters the LOS exists over the full orbital period and all low resolution information is transmitted in real time. Therefore, half the period is available for high resolution transmission which, at 100 KM altitude, is equal to 59.1 minutes. At an altitude of

500 KM this period is increased to 79.5 minutes. Since the read-out and transmission is limited to a 1 MC rate, the high resolution storage unit must be capable of recording for $\frac{59.1}{4.32} = 13.7$ minutes. The required low resolution storage capacity is a function of the area of lunar surface which is occluded because of loss of LOS. This quantity is relatively independent of altitude, except for the impact of altitude on sight line stability. This is depicted in the curves of Figure 5.14 . During new moon low resolution information must be continuously recorded for 46.6 minutes in each orbit.

In order to prevent contamination of the lunar environment, it is expected that all VOIS equipment including the video storage unit, must undergo a sterilization cycle equivalent to a 24 hour "soak" period at a temperature of 125°C.

The requirements discussed above were consolidated and included into a preliminary specification. Rough estimates of the maximum permissible weight and power drain of the storage unit were also included, and the specifications were forwarded to several prominent manufacturers of magnetic video storage equipment.

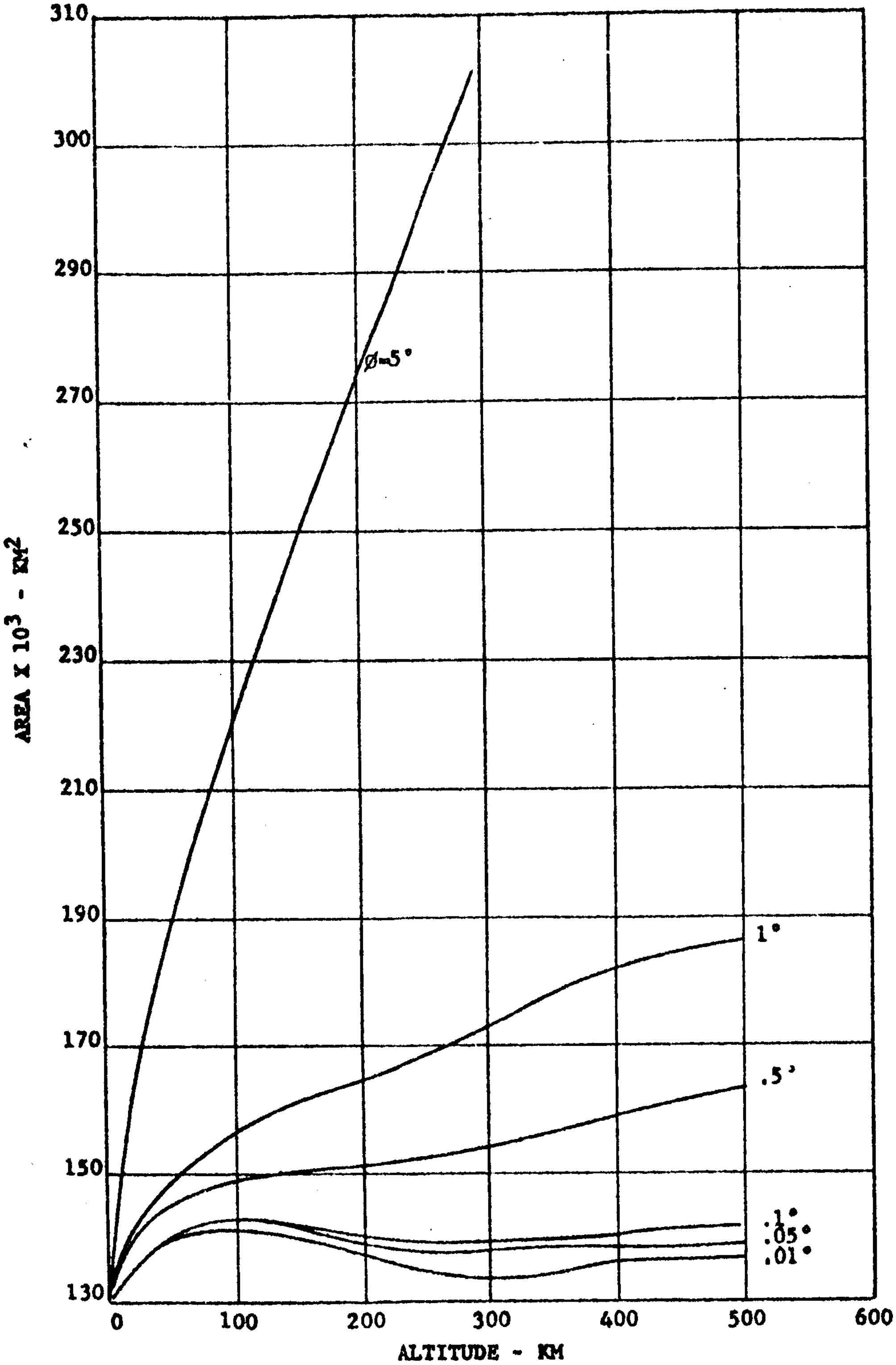


FIGURE 5.14

LUNAR SURFACE AREA WHICH MUST BE STORED VS. ALTITUDE VS. ROLL ANGLE Ø

Enthusiastic response was received from Ampex Military Products Company, Consolidated Electrodynamics Corporation, and Shepherd Industries, Incorporated, each expressing the fact that the storage system indicated by the specification was within the present state of the art.

The most comprehensive response was received from the Ampex organization in their description of a recorder-reproducer which they are presently developing under contract to the Goddard Space Flight Center of the National Aeronautics and Space Administration. This machine is a low power, lightweight video recorder-reproducer designed for spaceborne use. A "helical scan" principle is utilized in this unit, permitting video recording with only two or possibly a single rotating magnetic head. This system offers a considerable reduction in complexity and power consumption over current video tape machines which require four rotating heads. Ampex estimates that this machine, in its final form, will consume 60 watts, weigh 70 pounds and occupy one cubic foot. A photograph of a breadboard model of the unit is shown in Figure 5.15.

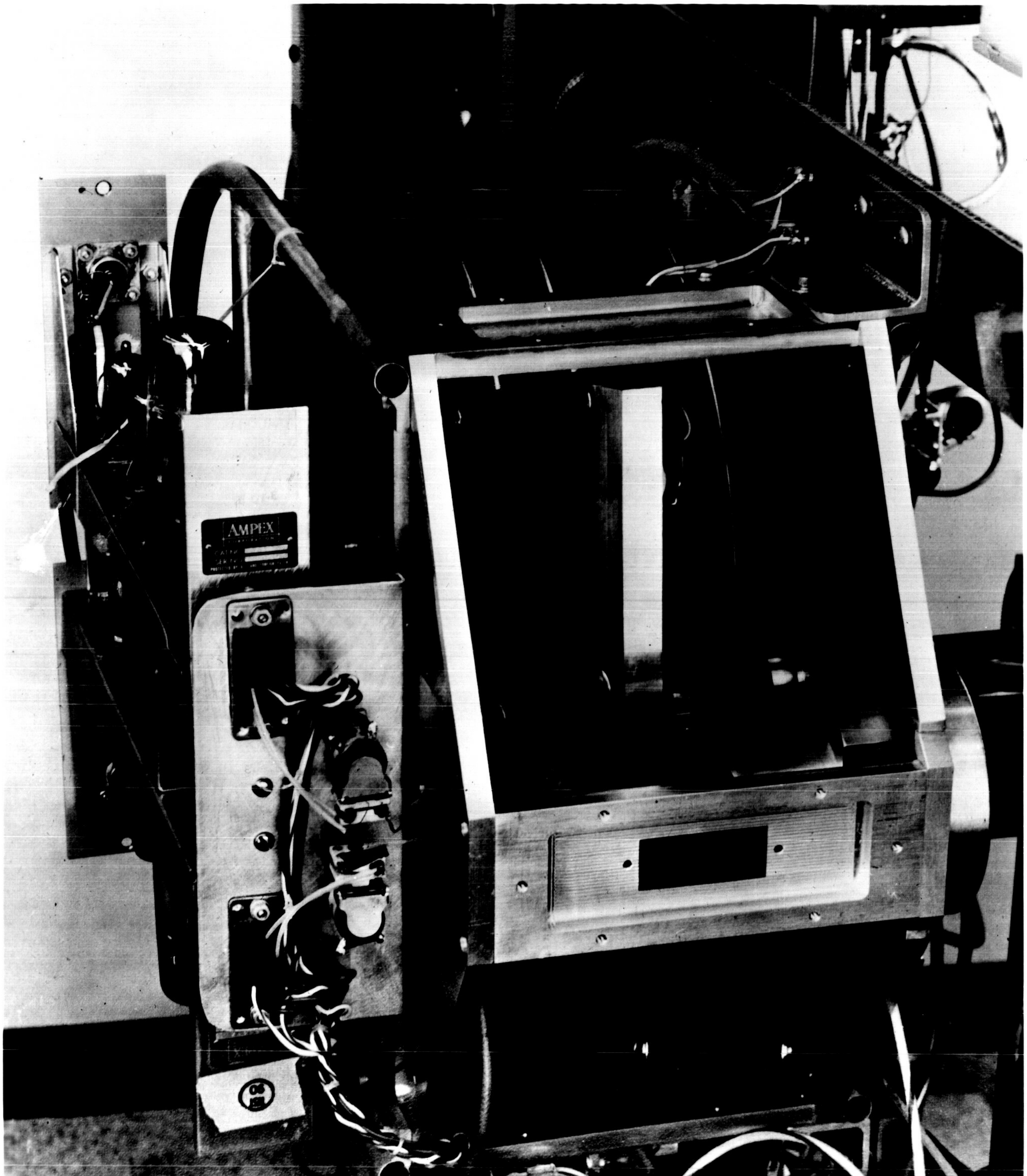


FIGURE 5.15
VIDEO RECORDER

Separate units will be required for the low resolution and high resolution channels, and the dimensions of the total video storage requirement for the VOIS system will be approximately as follows:

power consumption	120 watts
weight	140 pounds
volume	2 cubic feet

The sterilization specification is most severe in its effect on mylar based magnetic tape. Apparently the bonding material between the magnetic coating and the mylar ribbon will not withstand the 125°C temperature. Ampex, however, disclosed a proprietary development program in which the magnetic material has been plated onto a metallic base. To date these experiments have been very successful and samples have withstood extremely high temperatures (much greater than 125°). Although development of this product is not, as yet, complete, Ampex Military Products indicated that small quantities such as that required by the lunar orbiter program will be readily available.

In summary, investigation into the area of video storage equipment for the VOIS system has yielded the following:

a) A recorder-reproducer which meets the VOIS system requirements is within the present state of the art.

b) A recorder-reproducer which is applicable to the system is presently under development for NASA at Ampex Military Products Company.

c) Three major organizations, prominent in the field of video recording, are keenly interested in a development of this type.

d) Ampex Military Products Company has, under development, a metallic magnetic tap which will withstand the environment required for sterilization.

5.1.6 Programmer-Switcher

The Programmer-Switcher must perform two basic functions in the VOIS equipment. They are as follows:

a) Convert programming information into time gates which control the operational status of the camera systems, recording systems, and transmitter.

b) Route the video information to and from the appropriate system components.

Whenever LOS exists, it is possible to control the VOIS functions from the Earth Station, however, during occluded periods, certain operations such as high resolution mapping requires advance programming.

It is also possible to provide sufficient space borne equipment to program the operation of the VOIS unit in accordance with the entire monthly schedule. Although the amount of electronic equipment necessary to accomplish this feat is great, the digital nature of the circuitry does not have a significant impact upon the over-all size, weight, and power consumption of the VOIS unit. However, system reliability may be impaired somewhat because of the addition of a large number of components.

Clearly, a compromise between the completely automatic and the Earth Station command system is dictated. It is obvious that automatic operation is mandatory for those periods when LOS does not exist. Typically, the high resolution subsystem must be advance programmed for five on-off cycles at specific instances during the period of occlusion in each orbit. It is desirable that these intervals be of variable duration and location to an accuracy of one second.

Clock pulses from the intervalometer provide a reference which, by binary division, may generate the gate signals for a given operation. The exact location in time, or the number of counts required for the occurrence of the desired operation can be determined by reading the proper number into the binary system. This read-in can be accomplished through the use of a shift register or, more simply, by injecting pulses into the binary system at a high rate. The characteristics of the command channel will have effect upon the choice of programming method.

The block diagram of Figure 5-16 depicts a small portion of a typical system for routing and controlling the recording, readout, and transmission of cartographic video data.

It is clear that further investigation is required in this area within the confines of the specific programming requirement.

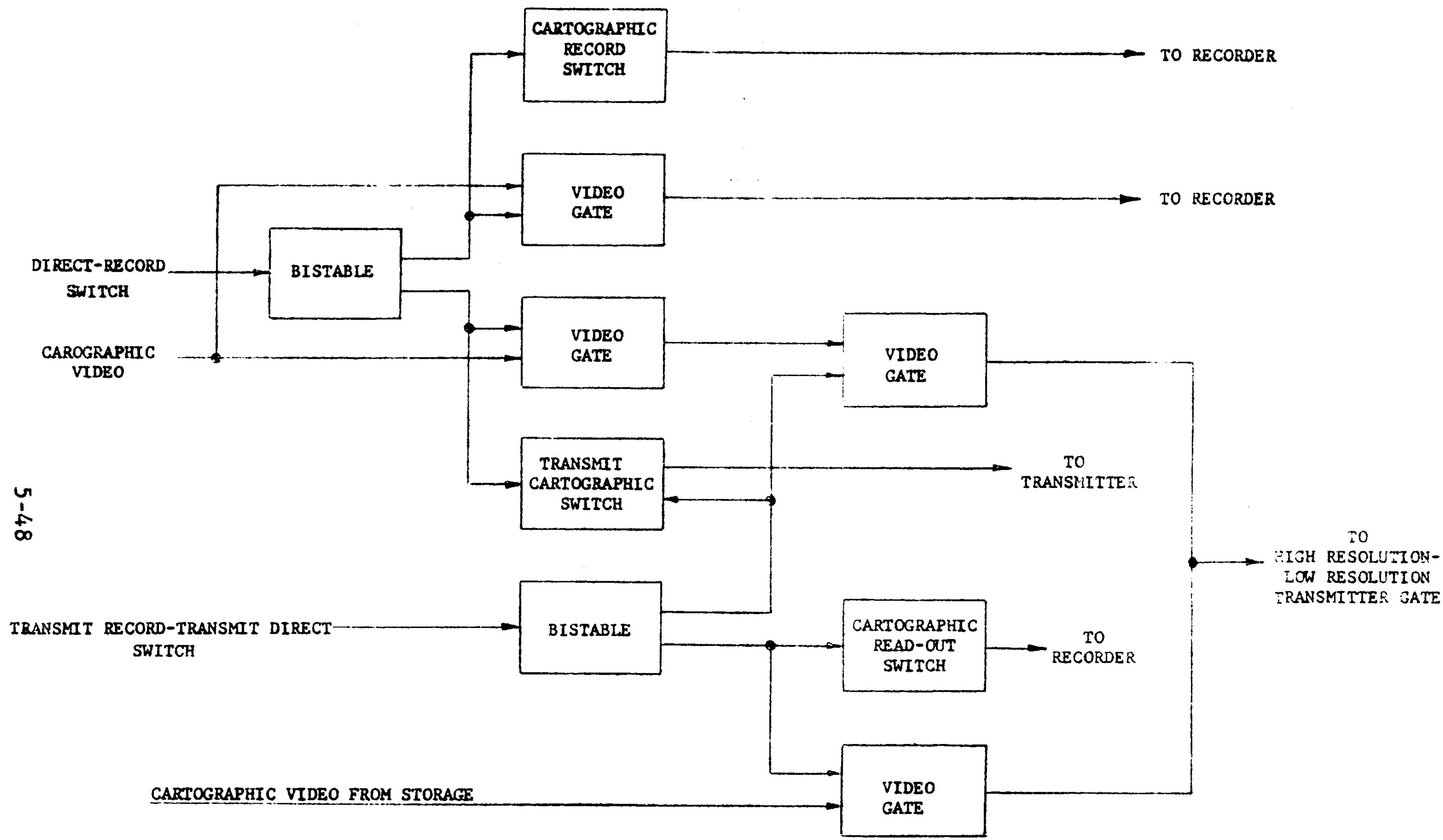


FIGURE 5.16

PORTION OF TYPICAL PROGRAMMER-SWITCHER

5.2 CARTOGRAPHIC MAPPING SUB-SYSTEM "B"

This sub-system will, in one sidereal period, collect the information necessary for the construction of a topographic map of the entire lunar surface in 30 meter resolution elements. In order to utilize the full 1 MC bandwidth for transmission of the data, which is collected at a comparatively low information rate, all video information must be stored. Upon completion of mapping, the stored information will be read out at a high rate. The time required for this transmission will be much less than that required for the data collection. The actual readout time will always be,

$$\frac{\text{orbital period}}{2} \times \frac{\text{transmission bandwidth}}{\text{collection bandwidth}}$$

Since the ratio of bandwidths for 30 meter resolution is approximately 1:10, the data from one complete pass will always be read out in the 709.6 seconds $\left(\frac{7096}{10}\right)$ immediately succeeding the completion of mapping.

This situation offers a considerable reduction in the amount of LOS time consumed by transmission of low resolution data. The resultant saving can be applied to transmission of high resolution information. Since LOS exists during 75% of the sidereal period, and 1/10 of the time required for mapping (50%) is required for transmission, low resolution transmission consumes only 5%. Therefore, the time available for high resolution transmission is approximately 75% -5% = 70% of the sidereal period (see 5.2.5).

5.2.1 Sub-System "B" Specifications

Elemental resolution	30 meters
Swath width	40 KM
Angle of view	20.4°
Objective optics	
Each linear fiber array	4 inch, f/3.5
V/H Sensor	12 inch, f/4
Number of linear arrays	2
Ground distance between stereo arrays	100 KM
Stereo angle	52°
B/H ratio	1
Number of elements/line	1333
Total number of elements simultaneously viewed	2666
Scan line spacing on lunar surface	21.4 meters
Scan lines/second	71.5

Video bandwidth (record)	95.7 KC
Video bandwidth (readout)	1.0 MC
Fiber size	.00085 inches
Total number of fibers	3734
Length of fiber line	3.175 inches
Outside diameter of fiber spiral	0.60 inches
Minimum number of cycles in spiral	2
Maximum area which can be mapped in high resolution	2.36×10^{12} square meters
Weight of optical system	20 pounds

5.2.2 Optics

5.2.2.1 Thirty Meter Triple Lens Camera

A cartographic optical system capable of surface resolution of 30 meters is discussed in this section.

The 30 meter optical system is of similar configuration to the 3 lens 10 meter unit discussed in Section 5.1.2.2. The mapping lenses in the 30 meter unit are calibrated, f/3.5 lenses with a focal length of 4 inches. The V/H sensor lens will still be the f/4, 12 inch lens illustrated. All previous analysis pertinent to the 10 meter, 12 inch unit is the same with the exception of weight and resolution. The new 4 inch unit weighs approximately 20 pounds.

5.2.2.2 Fiber Optics

The fiber optics arrangement for the 30 meter cartographic subsystem is similar to that of 10 meter subsystem, however, the quantitative dimensions differ.

For 30 meter resolvable elements,

number of elements simultaneously viewed	2666
total number of fibers	3734
length of fiber line	3.175 in.

Based on the above constants, a two turn spiral, possessing a .0216 inch thickness is required.

5.2.3 <u>Photosensor</u>

The vidicon for the 30 meter system is essentially the same as that for the 10 meter system except for minor modifications in the photo surface.

Since the scan rate of the 30 meter system reduces to

71.5 lines per second, the charge integration time is increased to $\frac{1}{71.5}$ seconds. Furthermore, the emitted energy from the 30 meter surface element is 10 times greater, and the optical aperture can be made greater than in the 10 meter case. This results in a still larger S/N than that in the 10 meter system.

It is conceivable, in view of the high incident illumination, that a relay lens, with its inherently low efficiency, can be utilized to eliminate the need for a fiber optics faceplate. The realization of this is dependent upon the severity of the mechanical registration problem, which may necessitate an integral fiber-vidicon unit.

The time constant of the photo-surface can be optimized for the particular scan rate utilized, however, a median value probably will suffice for both of the suggested cartographic systems. The configuration of the spiral pattern must, of course, be compatible with the two cycle spiral dictated by the 30 meter system.

5.2.4 Camera Auxiliary

The Camera Auxiliary for the 30 meter cartographic subsystem performs the same function as that in the 10 meter system and consists of the same basic units.

5.2.4.1 Preamplifier and Video Processor

The preamplifier for the 30 meter system is quite simple from a design standpoint, since the upper frequency response is less than 100 KC. In general, the comments that are made with reference to the 10 meter system are applicable here.

The actual frequency response figures for the 30 meter subsystem are 2.4 cps and 95.7 KC. The video processor differs slightly from that shown via Figure 5.10 as a result of change in bandwidth. The need for high peaking circuitry is eliminated since comparatively little upper frequency degradation is anticipated. Additional care must be given to preserving the low frequencies, therefore the signal emerging from the preamp is clamped immediately. All subsequent amplification of the video signal is performed by direct coupled stages.

5.2.4.2 Timer-Sync Generator

For the 30 meter cartographic subsystem, the Timer-Sync Generator is identical in function and configuration to the 10 meter subsystem.

The master frequency is, in this case, derived from a 142 cps sinusoid oscillator which, by 2:1 frequency division, synchronizes the 71 cps line rate generator. The pulse generation circuitry is identical to that of the 10 meter subsystem except for adjustment of the pulse widths.

5.2.4.3 Deflection Generator

The Deflection Generator for the 30 meter cartographic subsystem is essentially the same as that for the 10 meter subsystem.

Since a two cycle spiral is required here, a 142 cps sinusoid is modulated by a 71 cps sawtooth. The circuit configuration is the same as before however, circuit constants will differ.

5.2.4.4 Power Supply

The Power Supply of the 30 meter subsystem is identical to that described for the 10 meter subsystem.

5.2.5 Video Storage

The video storage requirement for the 30 meter cartographic system differs from that of the 10 meter system. Since the information rate for 30 meter surface elements is low (95.7 KC) in comparison to the possible transmission rate (1 MC), all cartographic mapping information will be stored. When mapping is completed in a given orbit, the stored information will be read out at a 1 megacycle rate.

The video storage equipment is required to record video information at a 95.7 KC rate for half the orbital period, or 59.1 minutes. This is the same as storage of 1 megacycle information for $\frac{95.7 \times 10^3}{10^6} \times 59.1 = 5.66$ minutes. The total tape footage required is therefore less than that required for 10 meter system. This storage requirement however, occurs in each of the 332 orbits, placing a greater burden on the magnetic tape from the standpoint of wear.

Since a relatively small portion of the LOS time is required for transmission of the 30 meter information, the time available for transmission of high resolution (1 meter) information is greatly increased. In the vicinity of first and third quarters, when LOS exists over the full orbit, 112.5 minutes of transmission time remain. Since the machine cannot conveniently record and reproduce simultaneously, the time required for recording must be subtracted from the total available time. Therefore, the video storage unit must have the capacity for recording information at the 4.32 MC rate for 21.1 minutes. This represents 1.55 times the tape footage for high resolution information as is required when a 10 meter cartographic system is utilized.

5.3 HIGH RESOLUTION SUB-SYSTEM

The high resolution line scan sub-system will electro-visually collect the information necessary to generate maps of selected areas on the lunar surface to an elemental resolution of one meter. This system will not provide topographical data.

The sighting line of this system is contained in a vertical plane perpendicular to the orbital plane and inclinded in such a direction as to scan that portion of the lunar surface previously mapped by the cartographic system. Selection of the specific areas to be mapped in high resolution, will be based upon examination of low resolution data collected on previous passes of the satellite.

The basic parameters of the high resolution sub-system are proportional to the ratio of its elemental resolution to that of the ten meter cartographic sub-system. The swath width of the high resolution system, for example, is reduced to 4.0 KM. All pertinent parameters are listed in the Table of Specifications.

Since the information rate of this sub-system is too great to be transmitted directly, all data must be stored and read out at a lower rate. The transmission time available for the stored high resolution information is that which remains after all cartographic data has been transmitted. The area, therefore, which can be mapped in one meter resolution elements is clearly dependent upon the transmission requirements of the cartographic mapping system. These requirements, which differ considerably in the ten meter and thirty meter systems, are discussed in Section 5.1 and 5.2 respectively. Regardless of which cartographic system is utilized, however, a minimum of 3.1% of the lunar surface can be mapped in one meter elements.

5.3.1 High Resolution Sub-System Specification

Elemental Resolution	1 meter
Swath Width	4 KM
Angle of View	2.3°
Objective Optics	120 inch, f/10
Number of Linear Arrays	1
Number of Elements/Line	4000
Scan Line Spacing On Lunar Surface	0.7 meters
Scan Lines/Second	2160
Video Bandwidth (Record)	4.32 MC
Video Bandwidth (Read-out)	1.0 MC
Fiber Size	.00085 inches
Total Number of Fibers	5600
Length of Fiber Line	4.76 inches
Outside Diameter of Fiber Spiral	0.60 inches
Minimum Number of Cycles In Spiral	3

5.3.2 <u>Optics</u>

5.3.2.1 Cassegrainian System

Figure 5.17 illustrates an f/10 Cassegrainian high acuity camera that is compatible with the objectives of the lunar orbiter program. In order not to exceed 200 to 300 pounds for total camera weight, lightweight construction techniques have been used throughout. Figures 5.18, 5.19 and 5.20 illustrate three techniques for fabricating extremely lightweight mirrors. Figure 5.18 shows a fuzed silicon blank having "umbrella rib" strengtheners. Figure 5.19 indicates a technique that consists of bonding pyroceram posts to a thin mirror face and a back up support. Additional strength can be gained by filling the space around the pyroceram posts with foamed material. The third mirror technique illustrated in Figure 5.20 shows a simple honeycombing of a portion of the reverse side of the mirror. The extra light mirror blanks weigh from one third to one half as much as conventional solid mirror blanks. The actual weight saving that can be achieved is dependent upon the acceleration to which the mirror will be subjected. Correspondence with one manufacturer of

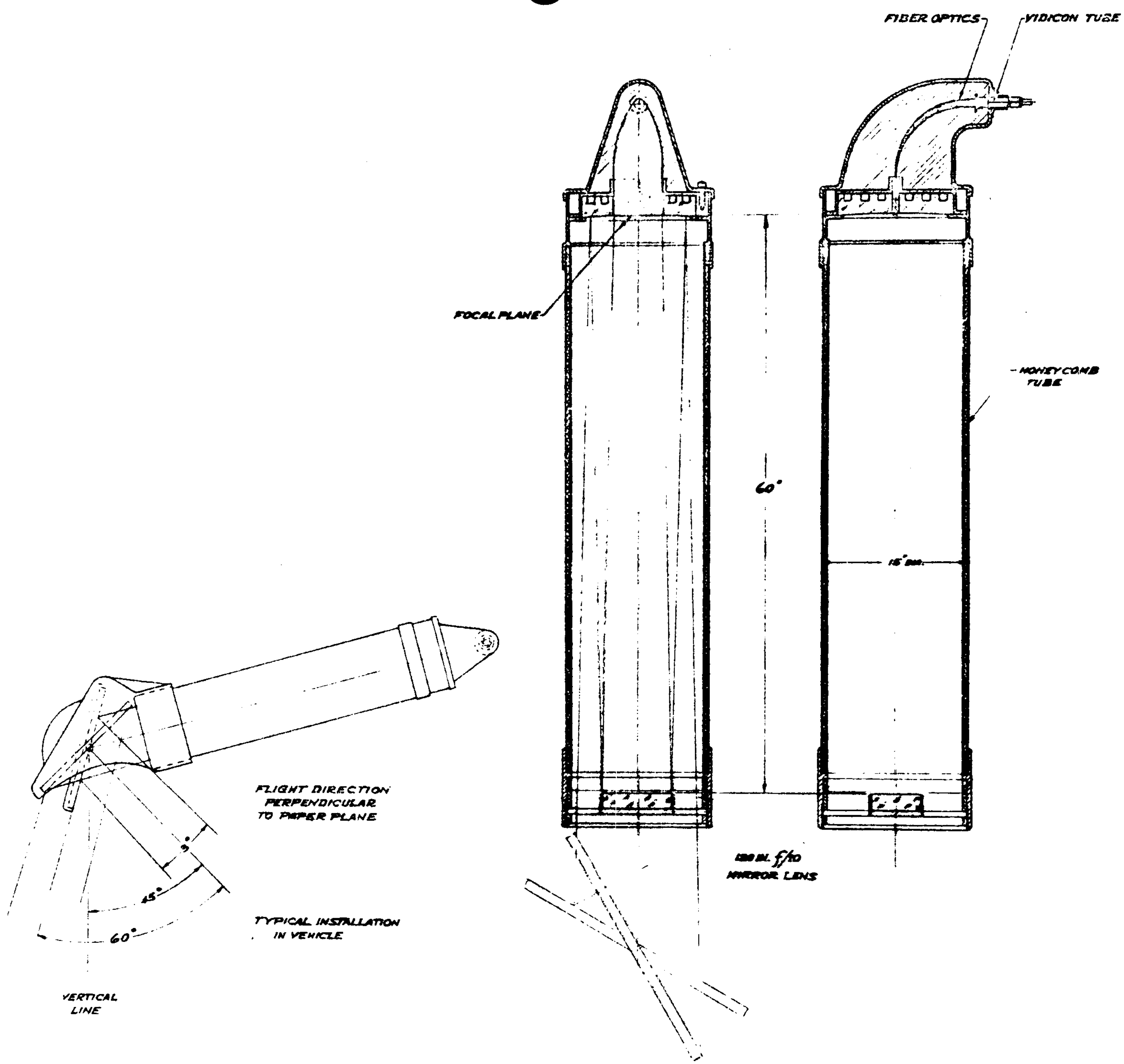


FIGURE 5.17

CASSEGRANIAN SYSTEM

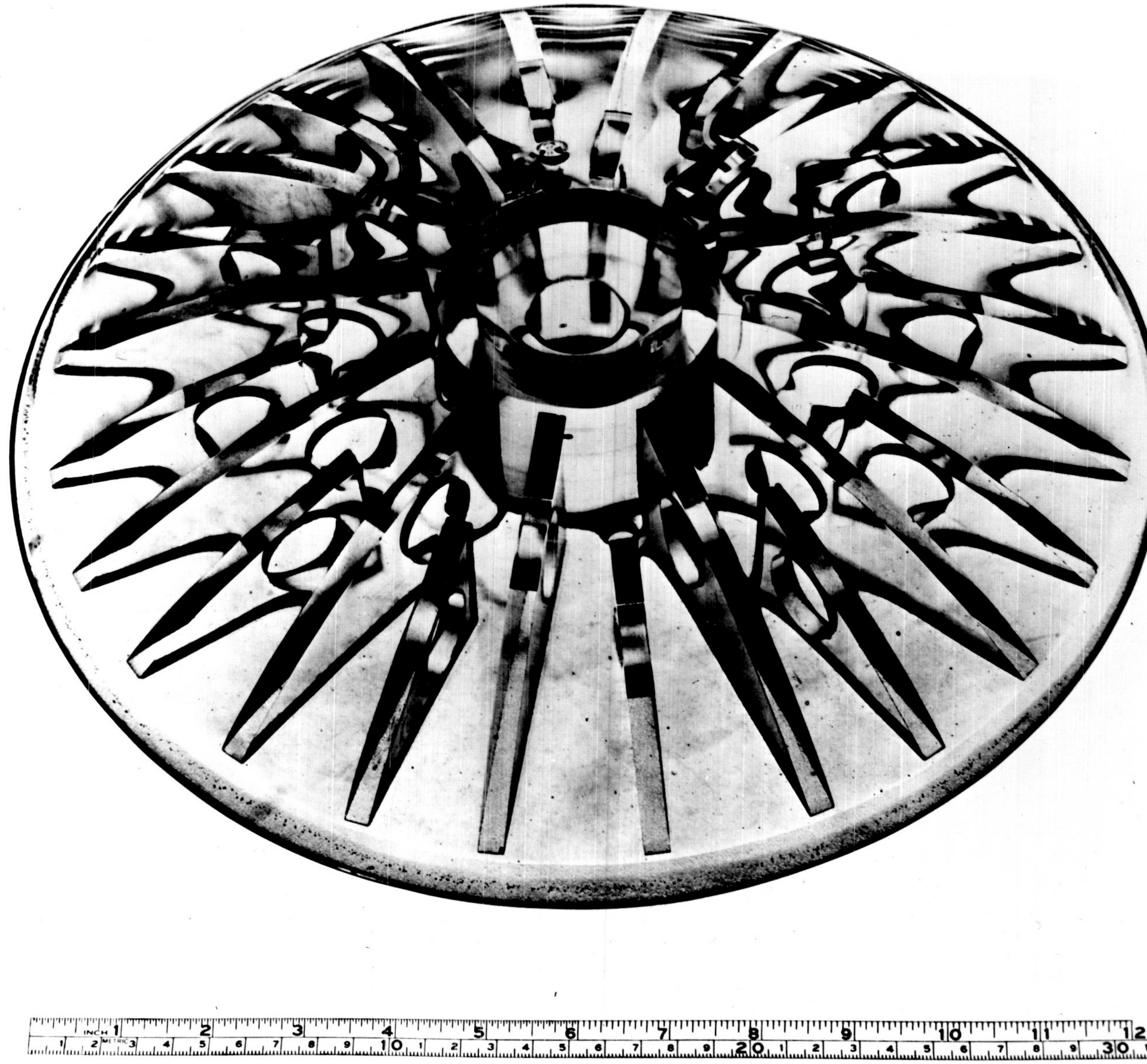


FIGURE 5.18

"UMBRELLA RIB" LIGHTWEIGHT MIRROR CONSTRUCTION

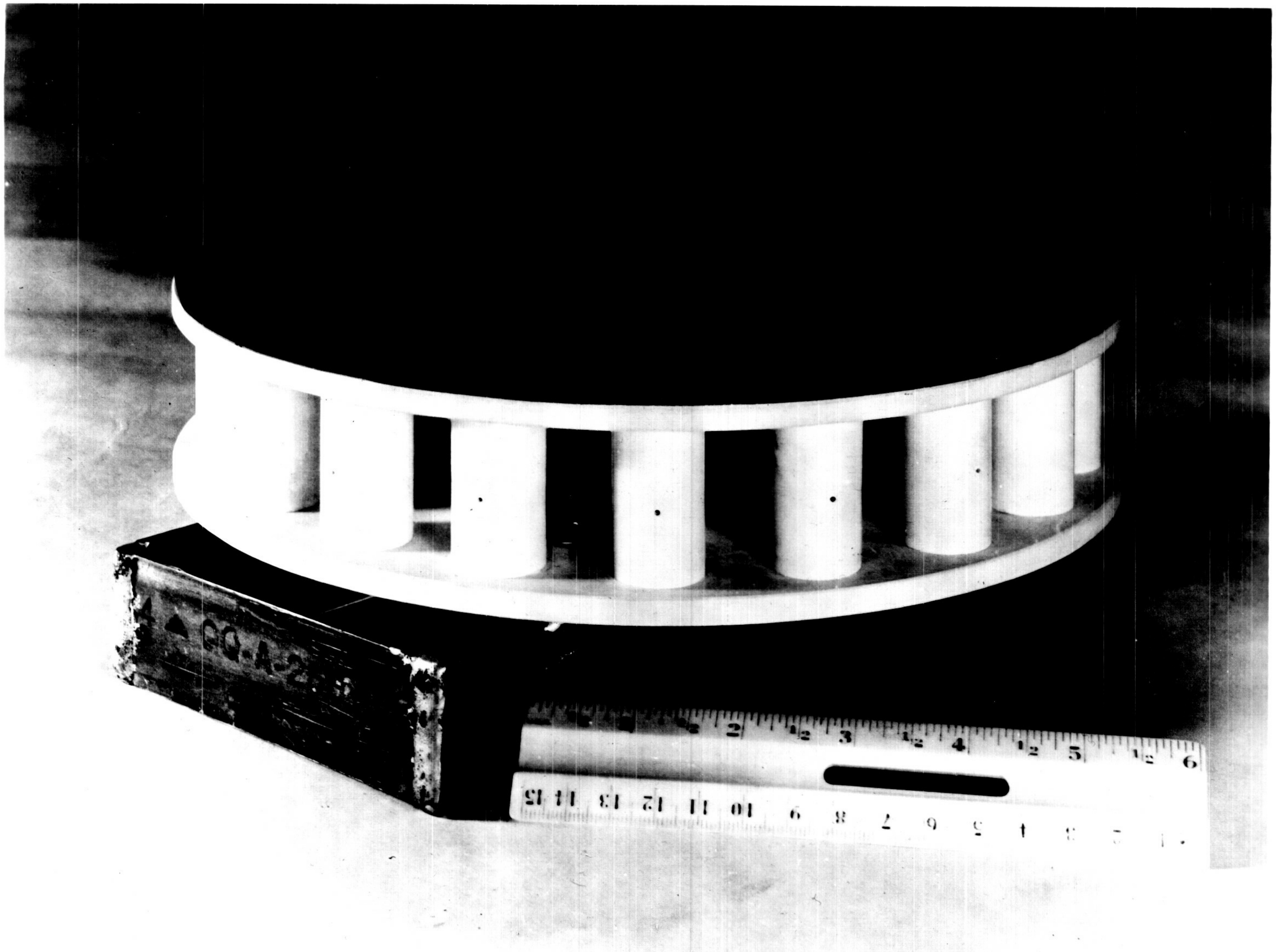


FIGURE 5.19

"POST" MIRROR CONSTRUCTION

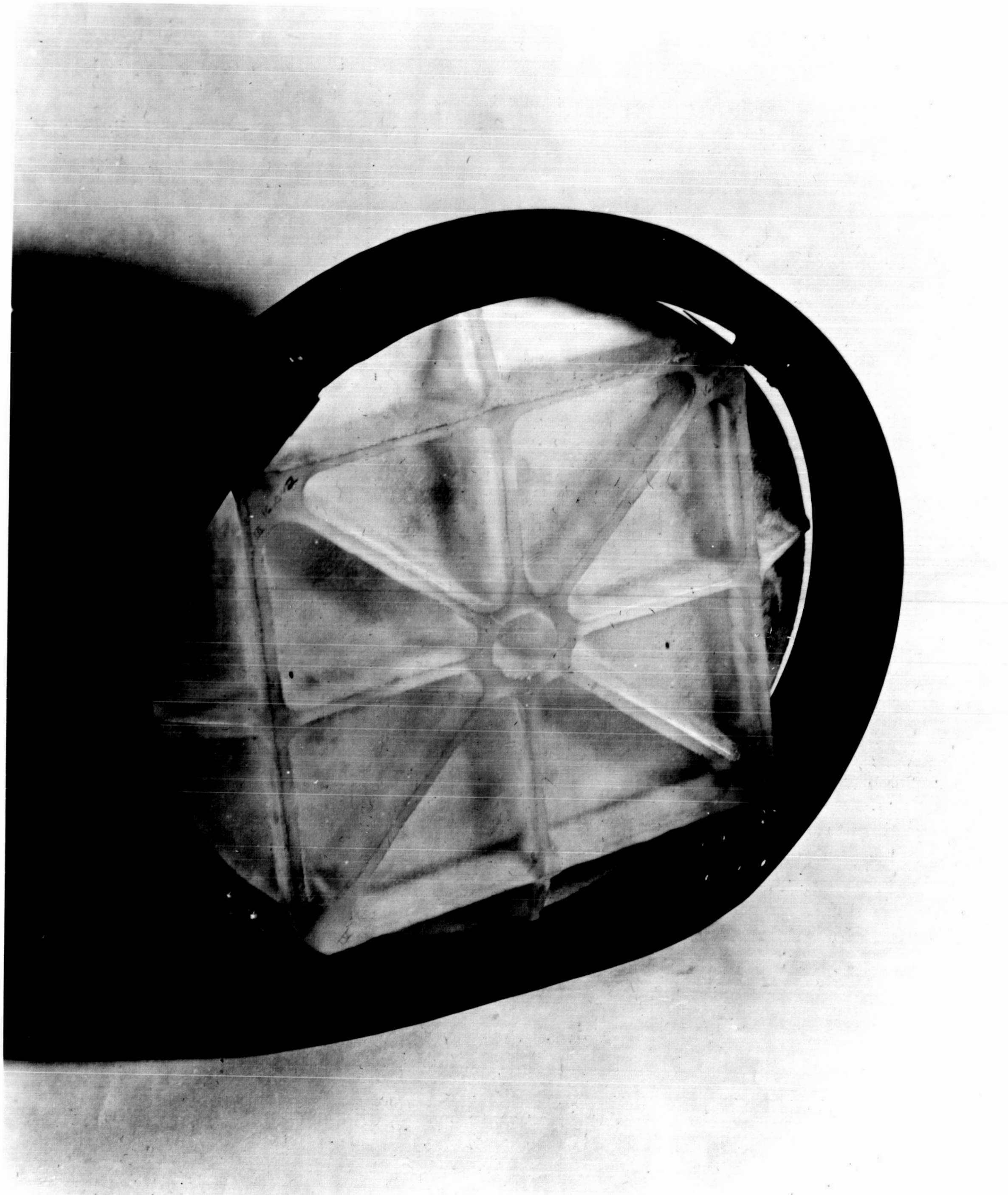
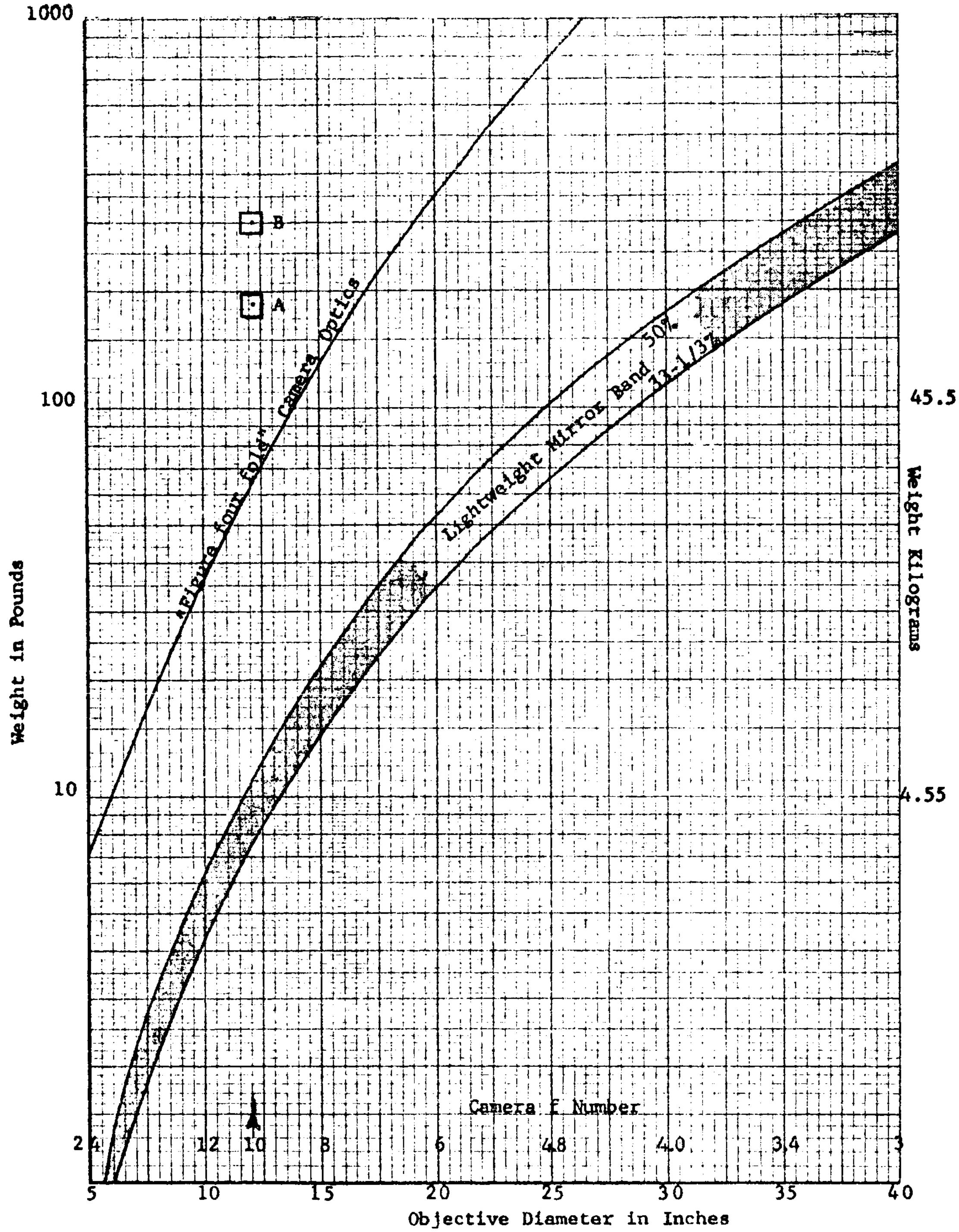


FIGURE 5.20

"HONEYCOMB" MIRROR CONSTRUCTION



B - Figure four fold
Refractor Camera

A - Cassegrainian
Camera

FIGURE 5.21

WEIGHT OF 120 INCH FOCAL LENGTH CAMERA OBJECTIVES AS A FUNCTION OF APERTURE these blanks indicates that mirrors up to 24 inches in diameter have been constructed that have withstood up to 10G accelerations with negligible deformation.

Figure 5.21 shows the weight range for these light mirror blanks as a function of mirror diameter. The aperture number (f) is also given for a Cassegrainian camera of 120 inch focal length constructed with a mirror of a particular given diameter. The secondary mirror in the Cassegrainian system is fixed in weight at 1.6 pounds and its dimensions and weight are independent of the primary mirror diameter.

As a general comparison of weight of glass between the reflector and a refractor systems, Figure 5.21 also shows the weight of glass for the equivalent "figure four fold" refractor camera that is discussed in the section.

The complete camera weights for the Cassegrainian and the Figure Four refractor are also given on Figure 5.21. These weights are indicated by points A and B.

Weight estimates for the high acuity Cassegrainian camera are as follows:

Mirror - 12" primary	11 pounds
Mirror - secondary	1.6 pounds
Camera barrel	25.5 pounds
Vidicon and fiber sensor	1.0 pound
Upper casting	8.0 pounds
Lower casting	8.0 pounds
Upper mirror housing	4.0 pounds
Lower mirror housing	2.0 pounds
Miscellaneous	2.0 pounds
	63.1 pounds
Camera Training Equipment	
Mirror and mirror housing	60 pounds
Casting, bearings framework	60 pounds
Mirror, rotation and drive linkage	10 pounds
	130 pounds

Therefore, the total camera weight is 63.1 + 130 or approximately 193 pounds (87.7 kilograms).

Advantages of the Cassegrainian system are:

The total weight of the Cassegrainian camera is approximately 110 pounds less than the equivalent refractor (lens) system.

The unit requires only three reflections from a mirror surface (compared with 4 in the Figure Four fold refractor). It is desirable to minimize reflections from mirrors in series, since each reflection introduces image degradations due to vibration of the mirror and imperfections in the mirror. The relative sensitivity of systems to these problems increases approximately by the square of the number of reflections required.

A mirror imperfection of 0.5 wavelength in 15 centimeters will cause the following image smear at the listed mirror to optical fiber distances:

Mirror to Fiber Distance	Image Smear
120 inches	11 microns
60 inches	5.5 microns
30 inches	2.7 microns

Mirrors can, in general, be "figured" to significantly better than 0.5 wavelength in 15 centimeters. Similarly, an examination of mirror vibration rates, shows that a rate of 0.4°/second rotational motion of a mirror 120 inches from the optical fiber sensor will cause only 10 microns of image smear in the time of exposure (approximately $\frac{1}{2160}$ seconds). This suggests that the system sensitivity to vibration and mirror imperfection will be small for good quality mirrors with reasonable vibration isolation.

The major disadvantages to the Cassegrainian high acuity system are as follows:

A) The Cassegrainian system does not readily lend itself to a more compact form. Folding the optical path is more difficult and subjects the images to the reflection degradations previously mentioned.

B) The presence of the small secondary mirror represents an obscuration in the optical aperture. This causes a loss of light plus an altering of the system high resolution characteristics. The resolution losses are significant only in systems operating in excess of 80 lines/mm. Light loss by obscuration with the 12 inch diameter mirror will be only 31%.

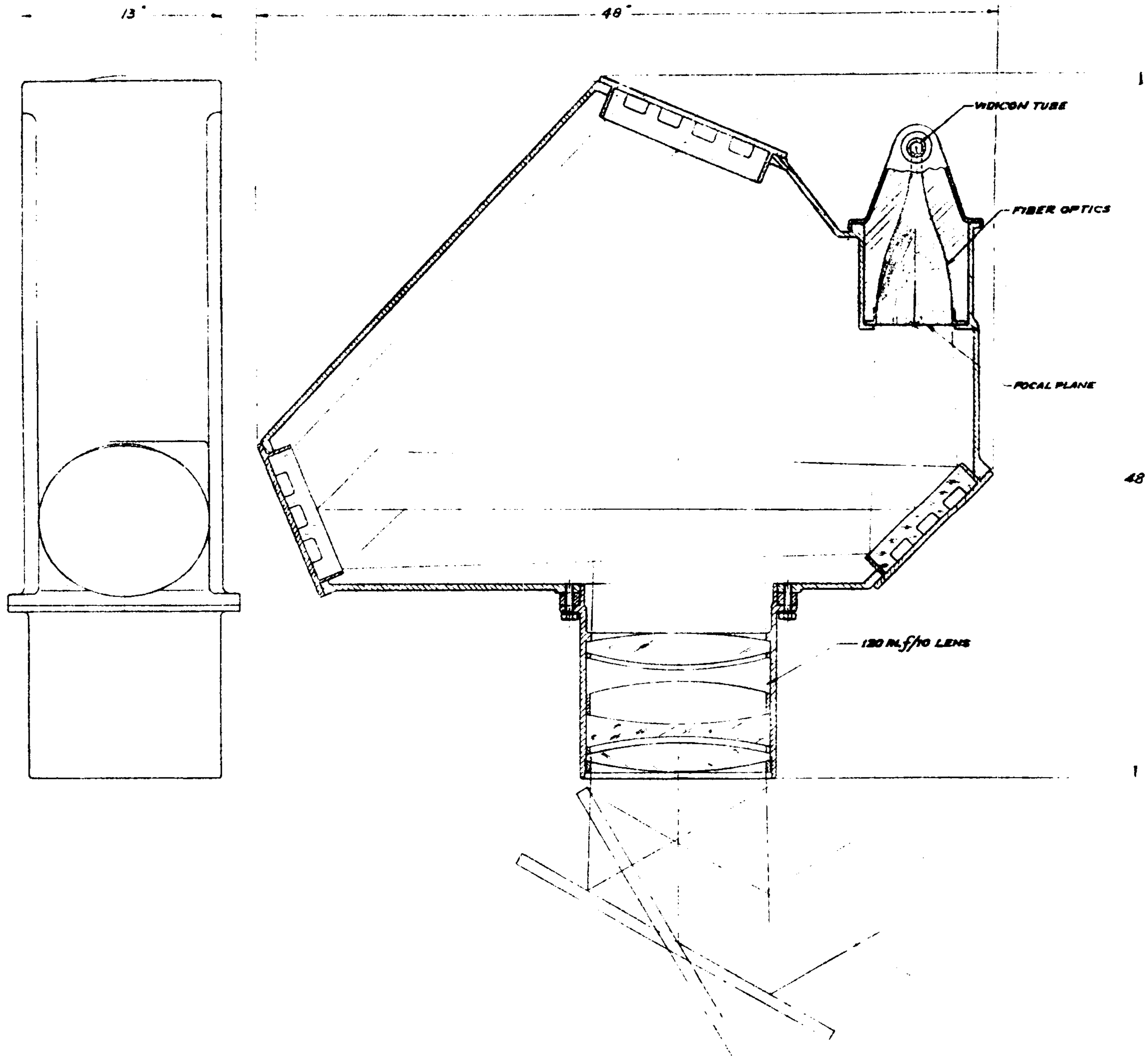


FIGURE 5.22

"FIGURE FOUR" FOLD REFRACTOR SYSTEM

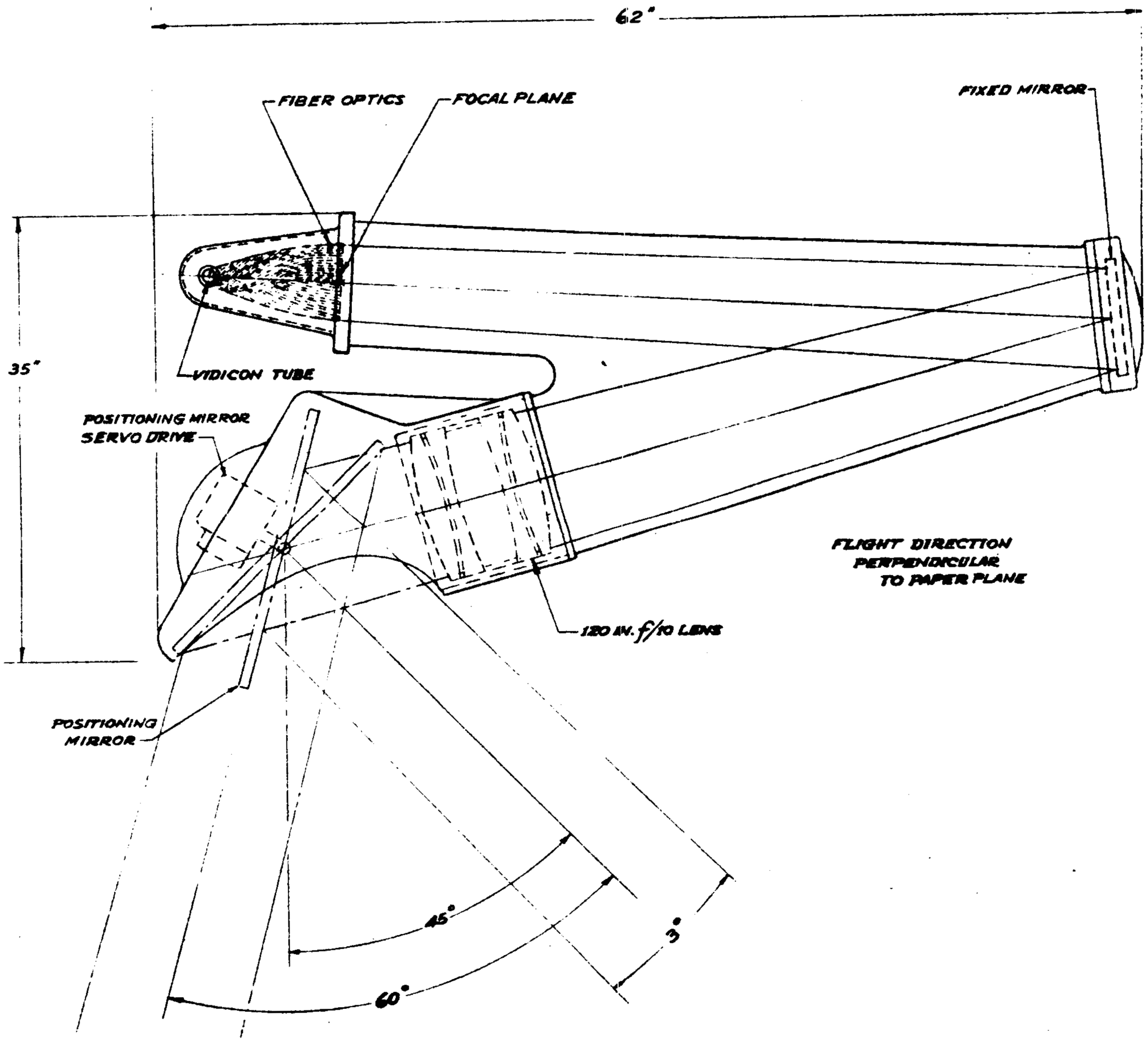


FIGURE 5.23

ALTERNATE REFRACTOR FOLDING TECHNIQUE

This redefines the system, slightly, as follows: f/10 - T/12 where T is the actual light gathering power of the system. It is significant to note that an equivalent f/10 lens will be about T/11 due to glass absorbtion and internal reflection losses within the lens.

5.3.2.2 High Acuity Refractor

Figures 5.22 and 5.23 illustrate two configurations for the high acuity refractor camera. The first diagram indicates the ease with which a camera having a narrow field of view can be compacted to fit into available space. The variety of this style (often referred to as "figure four fold") of folding a camera is quite large and Figure 5.22 is not to be interpreted as the only or best folding technique. One major disadvantage to the resulting camera is the multiplicity of reflections that result. Note that one additional reflection occurs at the training mirror surface. Thus the illustrated camera has a total of 4 reflections. With each reflection the image quality is somewhat degraded due to mirror surface imperfections and mirror vibrations. However, systems have been constructed with three internal reflections that achieve resolutions in excess of 100 photographic lines/mm under operational conditions.

Figure 5.23 illustrates a simpler configuration with a single fold. This results in a camera with a longer aspect ratio, comparable with the Cassegrainian system.

In all cases discussed the mirrors would be the lightweight type. However no lightweight technique exists for fabricating a lens. The lens contemplated would be a modified Petzval or Cooke triplet. Due to the narrow field of view and lower resolution requirements, this type of lens is suitable for the high acuity camera. The weight saving is quite significant with the contemplated lens. An equivalent lens resolving 150 photographic lines/mm over a 10° field will weigh 395 pounds in glass alone. The Petzval or Cooke triplet suitable for the Lunar Orbiter will weigh an estimated 50 pounds. Considering the weight limitations of the VOIS package this savings becomes quite significant.

The estimated weight for the camera illustrated in Figure 5.22 will be:

Optics (lens plus internal mirrors)	62 pounds
Camera casting	50 pounds
Side and end cover	50 pounds
Vidicon plus fiber sensor	1 pound
Mirror housings	7 pounds
Miscellaneous	2 pounds
	172 pounds
Training and pointing equipment, plus mirror	130 pounds
	302 pounds (136.5 K_g)

Each additional vidicon/fiber sensor added for reliability redundancy will increase the camera weight one pound each. The single fold camera illustrated in Figure 5.23 will weigh approximately the same as the multifold unit.

The advantage of the refractor camera lies primarily in the possibility of packaging the unit into a more compact form than the Cassegrainian camera. The packaging technique is also somewhat flexible so that better use may be made of existing space.

The major disadvantage of the unit is its weight, which is approximately 100 pounds more than the equivalent Cassegrainian system. This is clearly illustrated in Figure 5.21. Therefore if more weight can be allowed for the high acuity camera, the Cassegrainian system will make more efficient use of the added weight allowance from the standpoint of light gathering power.

5.3.2.3 Fiber Optics

The configuration of fiber optics for the high resolution sub-system differs from that of the cartographic sub-systems in the fact that only a single linear array is required. As stated previously, the 1 meter sub-system will not provide stereo coverage.

For 1 meter resolvable elements,

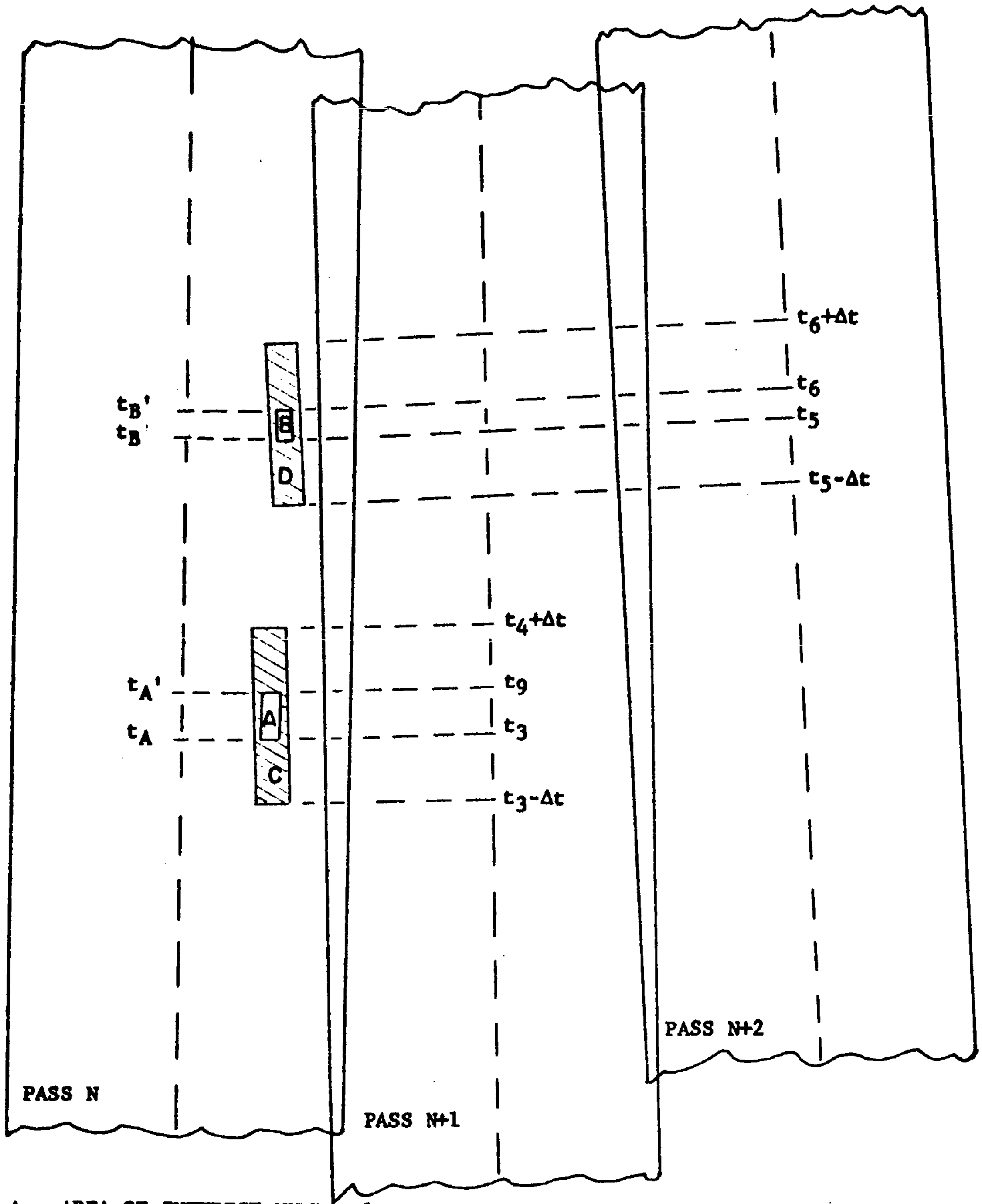
number of elements per line	=	4000
total number of fibers	=	5600
length of fiber line	=	4.76 inches

Based upon the above figures, a three turn spiral, having a thickness of .0325 inches is required.

5.3.3 Camera Pointing Control

The high acuity camera must be trained to scan predetermined sections of the lunar surface as the area is swept out beneath the satellite's path. Calculations indicate it is desirable to be able to scan from 12° in the direction of orbit precession to 45° in the direction of previously covered area in a plane perpendicular to the line of flight for a 100 KM vehicle altitude. This gives the camera complete coverage of the current swath plus the previous two swaths at the lunar equator. Coverage capability for the area immediately below the satellite is important near the poles where the coverage swaths will converge. In order to achieve this range of scanning (-12 to +45° or 57° total) either the camera must be slewed or a training mirror incorporated. The latter is felt to be the best solution for the training requirements. Available space within the vehicle will undoubtedly be too limited to allow adequate free space through which to slew the camera cylinder through 57° to obtain the necessary pointing coverage.

The exterior training mirror illustrated in Figure 5.17, 5.22 and 5.23 is movable about only one axis so that the camera can be pointed only within a plane perpendicular to the direction of flight. A discrete area to be observed by the high acuity camera will therefore be specified as an angular deviation from the vertical on a subsequent pass and an interval of exposure time. Attitude irregularities of the satellite may also be compensated for by corrective motion of this mirror. The time interval specified for high acuity exposure will be long enough to ensure coverage of the desired area (see Figure 5.24). This figure illustrates a typical coverage pattern for two areas of interest, A and B. These are intercepted by the cartographic camera at times t_A to t'_A for area A and t_B to t'_B for area B during pass N. The distance from the nadir line (dashed) to the center of the areas of interest can be readily determined. From these values the distances between the areas of interest and the nadir traces for subsequent passes (pass N + 1 and pass N + 2 illustrated) may be calculated. One can readily determine the required angular displacement for the training mirror to allow observation of the lunar surface areas



A - AREA OF INTEREST NUMBER 1
B - AREA OF INTEREST NUMBER 2
C & D - HIGH ACUITY COVERAGE SWATHS

FIGURE 5.24

TYPICAL HIGH RESOLUTION COVERAGE

of interest on subsequent passes. The times for intercept (t_3 to t_4 for area A and t_5 to t_6 for area B) are obtained from knowing vehicle period and orbit parameters. Correction for the time lead or lag due to the intercept with a forward or aft looking observation plane and the time of interception for the plane perpendicular to the orbit is implied.

An uncertainty of $\pm\Delta t$ will exist in the accuracy of prediction of intercept times for subsequent passes. To ensure coverage, the high acuity camera will begin observation Δt before the calculated intercept time and continue Δt beyond calculated shut-off. The swaths thus observed are illustrated in Figure 5.24. Area A is observed on the subsequent pass (pass n + 1) and area B is observed two passes after initial intercept (pass n + 2). This camera programming will require an intervalometer with an accuracy of one part in 4320 and a precision of 0.5 seconds. The intervalometer can be reset or checked once every orbit or two hours. With the 45° side slewing capability the camera can observe any detail within the last two passes at the lunar equator, last 4 passes at ±60° latitude and last eight passes at ±76° latitude. Observation of detail on the current swath immediately below the vehicle is possible, however programming would be difficult even in cases where read-out during line-of-sight is used unless the area has been seen on previous passes. When line-of-sight contact exists it is entirely possible to slew the high acuity camera to an area observed by the forward looking scan of the cartographic camera assuming command data read-in is possible during cartographic data read-out. For a vehicle at 100 KM altitude the time between observation of an area by the forward looking cartographic scan and intersection of the same area by the scan plane for the high acuity camera would be 50 KM divided by the satellites projected surface velocity

$$(\frac{50 \times 10^3 \text{ meters}}{1540 \text{ meters/second}} = 32.5 \text{ seconds.}$$

This response time is probably too short for an earth observer to digest the data and make required conversions of lunar surface coordinates of the area of interest to angle and time coordinates for the high acuity telescope. However, the same area is available at very little degradation from 2 to 8 passes later which allows from 4 to 16 hours for decision making and command data conversion. If the area of interest is left to be observed until the camera must be trained to its full extreme of 45° to the side, the surface resolution will be degraded from 1.0 meter to 1.4 meters. In reality the limit of camera side excursion is by no means limited to 45°. However, the resolution begins to fall off rather severely beyond 45° due to the increase of the range to the area of interest. In addition, at greater angles the curvature of the lunar surface adds significantly to the range increase and observational obliquity at these greater angles.

The impact of attitude and altitude control on the high acuity camera pointing control and ground coverage is discussed in detail in section 4.1.

5.3.4 Photosensor

The high resolution sub-system specifications dictate a vidicon with an extremely short lag characteristic since a scan rate of 2160 lines per second is required.

From a one meter square surface element, 9.8×10^3 lumens or 9.8×10^{19} photons are emitted. In the worst case, the surface element is viewed at a 45° angle, therefore $n = 2.81 \times 10^9$ photons per second per square meter (see 5.1.3).

Since the optical aperture in this case is .0728 square meters, the optical transmission factor is 0.7, and the integration time is 1/2160 seconds, 9.39×10^4 photons enter the aperture. A 10 percent conversion efficiency yields 0.939×10^4 electrons and a primary S/N of 97.8. This number is considered to be respectable, however, additional margin exists in the fact that the optical aperture can be increased.

The registration pattern for the high resolution sub-system vidicon must be compatible with a three-cycle spiral.

5.3.5 High Resolution Camera Auxiliary

The camera auxiliary for the one meter sub-system performs the same function as those in the cartographic sub-systems and consists of the same basic components.

5.3.5.1 Preamplifier And Video Processor

The same general comments as were made for the cartographic systems apply to the preamplifier of the one meter sub-system. Additional care, however must be given in this case because of the increased bandwidth requirements. Since the quantities contemplated for this program are relatively small, it is practical to individually select transistors on the basis of noise level for the preamp input stage.

The video processor configuration is identical to that of the 10 meter system, however, the individual circuitry must be compatible with the bandwidth requirements. The actual frequency response figures for the high resolution sub-system are 4.32 MC and 73 CPS. Neither of the figures are worthy of great concern for the circuit designer.

5.3.5.2 Timer-Sync Generator

The timer-sync generator for the one meter sub-system is identical in function and configuration to that of the cartographic sub-systems except for differences in rates.

The master frequency is derived from a 7480 CPS oscillator which supplies the sinusoid to the deflection generator. A 3:1 frequency divider synchronizes a 2160 CPS line rate pulse generator.

5.3.5.3 Deflection Generator

The high resolution deflection system is the same as that for the cartographic sub-systems, except for the frequencies involved. A three-cycle spiral is generated, in this case, at a 2160 CPS repetition rate. The sinusoid rate is therefore 7480 CPS.

5.3.5.4 Power Supply

The power supply for the high resolution sub-system is identical to that described for the cartographic sub-system.

5.3.6 Video Storage

Storage of the high resolution video information is discussed in detail under sections 5.1.5 and 5.2.5.

5.4 V/H SENSOR

A V/H Sensor will be provided which occupies the central portion of the field of view of the cartographic camera subsystem, between the stereo lines (See Figure 5.3 and 5.6). This sensor is an integral unit previously designed at Du Mont Military Electronics and is described in detail in Appendix A.

5.5 MECHANICAL CONSIDERATIONS

In applications involving space experimentation, size and weight are precious commodities and must be carefully considered. Once the basic system has been established, it is possible to minimize the weight contributions by using good design practice. However, size or volume is generally determined by the principle elements. With this in mind, the form factor of the VOIS lunar orbiter was developed, as shown in Figure 5.2.

The design concept incorporates the vidicon tube, camera auxiliary equipment as part of their respective objective lens systems. The vidicon face plate, which is optically flat, will be located accurately to a reference surface in the lens housing. A supporting frame will provide mounting for the lens system, along with provisions for mounting the timer-program control, signal switching unit and the dual channel magnetic storage equipment. The frame must be constructed not only to facilitate the assembly procedure but to provide a means of mounting without inducing stresses into the optical path resulting in degradation of information.

The design philosophy used for component packaging will follow a concept which has been proven in past designs and is generally considered as satisfying the requirement of high strength-to-weight ratio. This design is developed around the general "I" beam structure. An example of this is shown in an artist's conception of a typical Camera Auxiliary Unit. See Figure 5.25. Electrical components are mounted on six (6) enclosed cast aluminum "I" beam chassis. As can be seen, this type of chassis design lends itself to use as a basic mold for potting. It is anticipated that a light weight foam potting compound will be used providing the dual function of electrical insulation and increased mechanical strength. Experience has shown that, for components supported in this manner, lead breakage and fatigue failure is virtually nil.

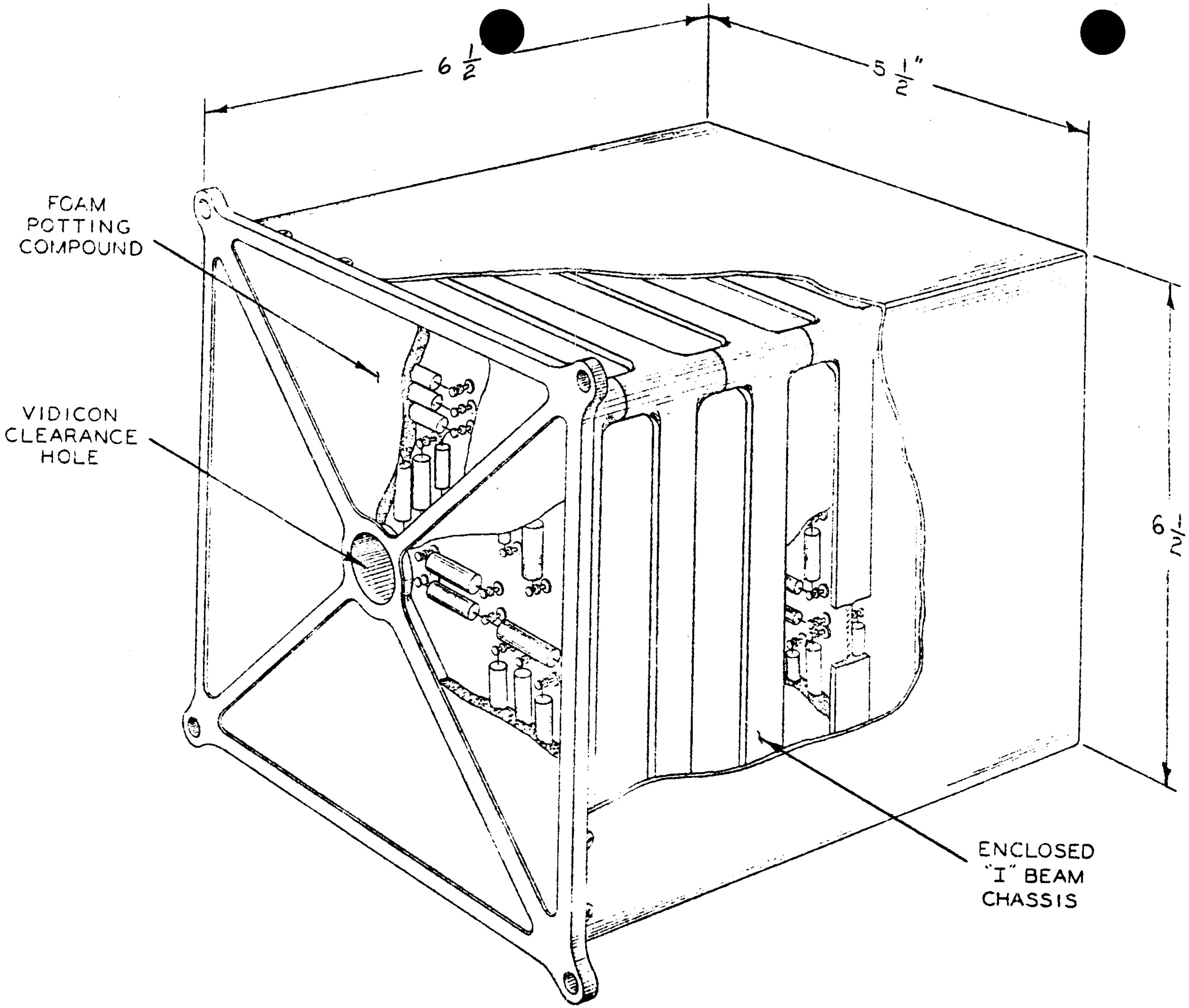


FIGURE 5.25

CAMERA AUXILIARY CONSTRUCTION

5.6 OVERALL SYSTEM DIMENSIONS

A diagram depicting a layout of the various components which may comprise typical VOIS units is shown in Figure 5.2. In the illustration, the 10 meter cartographic subsystem and the 120 inch Cassegrainian optical system are shown. It is obvious that the overall physical dimensions of the system are primarily determined by the high resolution system. Therefore, the impact of choice between the 10 meter and 30 meter cartographic systems is insignificant. However, the particular high acuity optical system which is chosen has a marked effect on the overall size and weight of the system. Factors governing this choice are discussed in Section 5.3.2.1.

The overall system dimensions are, therefore,

Weight	425 lbs.
Size	60 X 24 X 40
Volume	33 cu. ft. (25% Packing Density)
Power Consumption	180 watts

6.0 CONCLUSIONS

One significant conclusion of this type of study is that much more remains to be done. This incompleteness of the initial study phase is not at all surprising. When one sets out to examine a totally new area or scientific frontier it is to be expected that as the understanding of the problem increases so does the awareness of new facets to the problem. The extent to which the new problems which constantly appear can be pursued or analyzed is a direct function of economics and time. Increasing the allotted time and money by a factor of 10 will result in a study of larger scope with greater depth in each new area. Undoubtedly, at the time of completion of an expanded study there would still be a great quantity of loose-end areas that require further analysis.

Therefore, in order to obtain information of value one must weigh the relative gains of deeper analysis against program objective, funds and schedule. Obviously, there must be a point of diminishing returns. One must, therefore, put the best possible effort on the problem by the most competent group for the limited time available. It is the conclusion of these authors that further study will add much more to the understanding of the problem. However, sufficient ground has been covered to enable a breadboard development to proceed along intelligent lines.

There can be no question as to the realizability of the exemplary systems described in Section 5. Furthermore, this line scan electronic camera adds a valuable new tool to the cartographic art. Unlike film cameras, the fiber optics sensor involves no moving parts. Because of the permanence of installation of the sensor, the camera inherently has extremely good metric qualities and can be very precisely calibrated. This enables a video sensor to be used in a highly desirable cartographic or metric mode heretofore impossible.

APPENDIX A

YAW ANGLE AND V/H SENSOR

The passive sensing of yaw angle must necessarily be accomplished by observation of distinguishable features on the surface of the moon, using either reflected or self-emitted radiation. A yaw sensor must, therefore, include an optical system imaging the terrain features, means for distinguishing and selecting certain of these features, and a suitable method of measuring the apparent velocity of the features with respect to a reference orthogonal coordinate system.

Sensor Principle

An image of the terrain is allowed to move across a ruled periodic grid of opaque lines which imparts a characteristic spatial modulation to the image. The image motion converts the light transmitted by the grid to a time modulated signal if the image contains contrasting regions of dimensions less than the pitch of the periodic grid. For a grid of pitch p used in an optical system of focal length F, the resulting frequency of the modulation is

$$f_m = \frac{V}{H} \frac{F\sin\theta}{p}$$

for an angular image velocity V/H at an angle θ with respect to the grid lines.

Each element of the image is chopped at the frequency f_m, and since contrasting elements will appear at random, the signal from the entire image will be the resultant of many components of frequency f_m but with random phase and amplitude. Computation of the resultant is analogous to a determination of the received signal in a radio scatter transmission system. Suffice to say the signal shows a Rayleigh distribution as shown in Figure A.1, with a position determined by the nature of the contrasting elements of the terrain.

Two grid reticles, oriented perpendicularly, as shown in Figure A.2, are used in establishing the angle of image motion with respect to the center-line of the array. An apparent image motion inclined at an angle ϕ to the center-line, as shown in Figure A.2, will result in an angle of interception on the grid of $(45° + \phi)$ for grid A and $(45° - \phi)$ on grid B. Individual detectors are used for the two grids, and the resulting frequencies f_A and f_B are

$$f_A = \frac{V}{H} \frac{F \sin(45° + \phi)}{p}$$

$$f_B = \frac{V}{H} \frac{F \sin(45° - \phi)}{p}$$

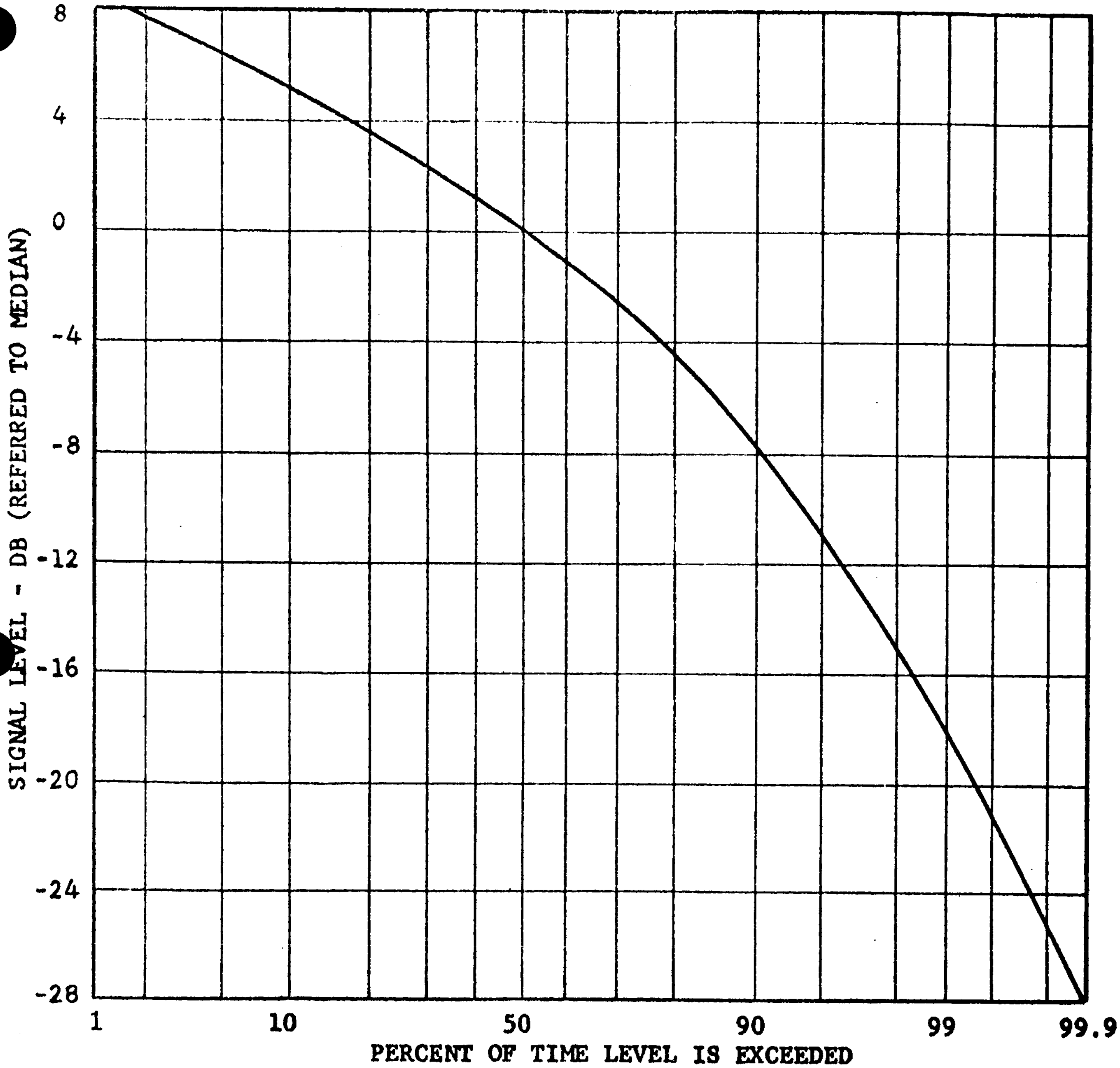


FIGURE A.1

RAYLEIGH DISTRIBUTION

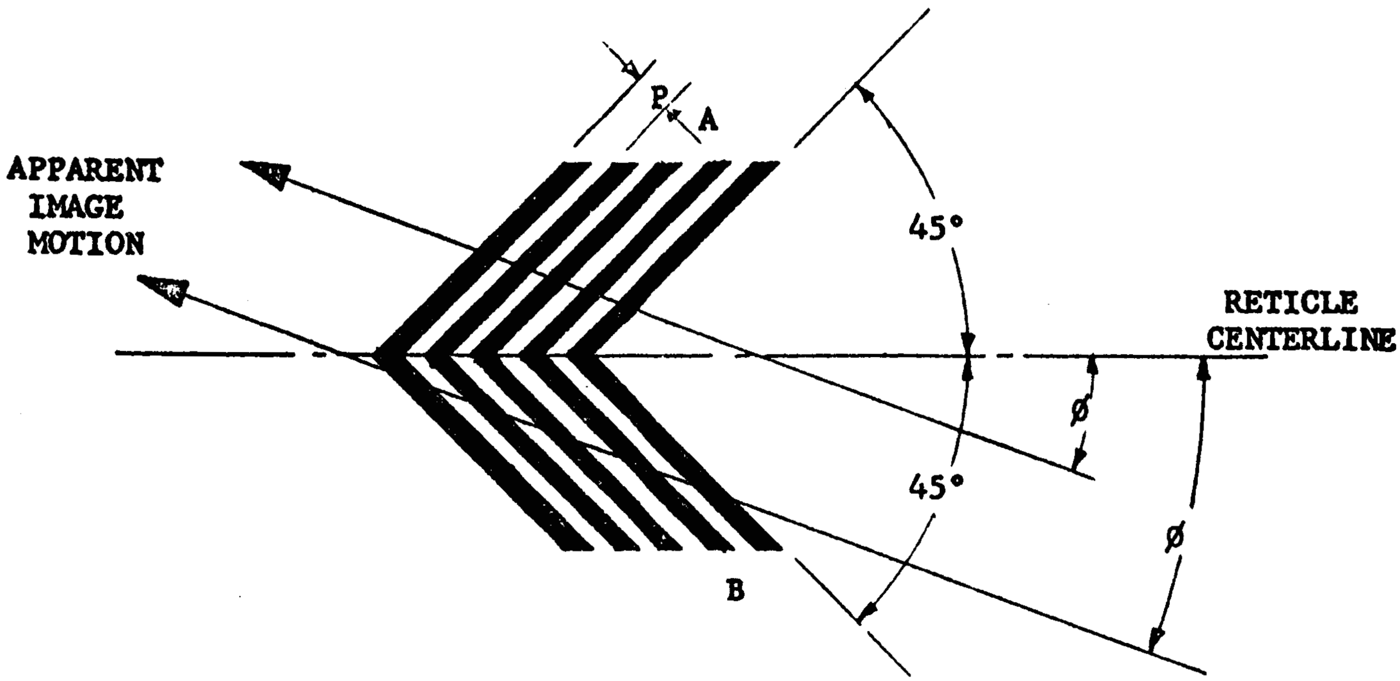


FIGURE A-2

RETICLE GRID FOR V/H SENSOR

where F is the focal length of the optical system, p the pitch of the grid lines, V the satellite velocity and H the satellite altitude.

The difference frequency

$$f_A - f_B = \frac{VF}{Hp}(1.4 \sin\phi),$$

is then a measure of the yaw angle, and can be employed to drive the grid reticle pair to align the reticle center-line with the apparent image motion, the sense being established from an observation of the relative magnitudes of f_A and f_B . A simple means of deriving the error signal may employ a reversible counter which is counted up by each cycle of f_A and counted down by each cycle of f_B. A sufficient counting interval may be selected to permit detection of a 2° misalignment at the most unfavorable extreme of V/H. Evaluating the difference frequency for the allowable 2° error at V = 1.14 KM, H = 500 KM,

$$f_A - f_B = 1.12 \times 10^{-4} \frac{F}{p}$$

With F = 12", p = .001",

$$f_A - f_B = 1.12 \times 10^{-4} \times 12 \times 1000 = 1.35 \text{ CPS}$$

If, in any 1.5 second counting period, the counter advances or counts back two cycles, yaw correction is applied.

If either exemplary system of section 5.0 is used, the above computation becomes

$$f_a - f_b = \frac{1.54}{100} \times \frac{12}{.001} \times 1.4 \times .035$$

Thus, a deviation of approximately 10 cycles in one second will cause yaw correction.

In areas with negligible contrast, holding circuits prevent the counter from deviating from reset position.

APPENDIX B

PHOTOMETRY

The choice of a photosensing device is primarily determined by the available energy incident upon the photosensitive surface. Although the energy which reaches the sensor is limited by the area of the collecting aperture, a knowledge of the total available incident energy can significantly narrow the area of choice.

Consider the configuration depicted in Figure B.1 where energy emanating from the source S impinges upon the interior of the hemispherical surface.

If $n = \dfrac{\text{photons}}{\text{area x seconds}}$,

$$n = n_o \cos\theta$$

where

n_o = the number of photons per unit area entering an aperture located on a line normal to the source surface.

The total number of photons per second incident on the hemisphere

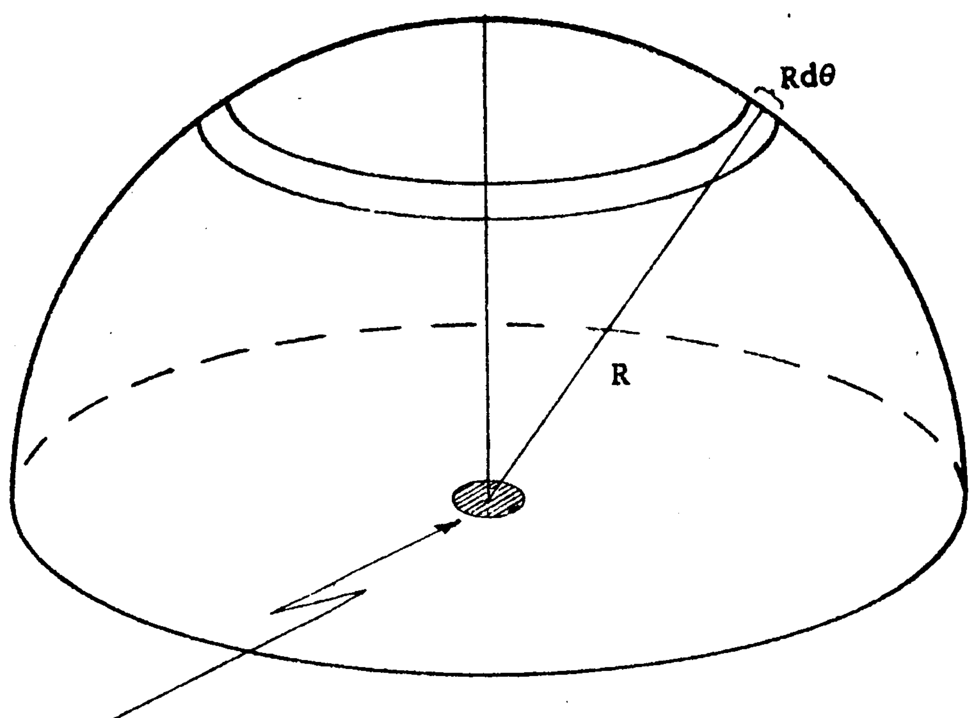


FIGURE B-1

RADIANT ENERGY DIAGRAM

is equal to:

$$N = \int_{\theta = 0^\circ}^{90^\circ} n_o \cos\theta \ (2\pi R \sin\theta) \ (R d\theta)$$

$$= 2\pi R^2 n_o \int_{0^\circ}^{90^\circ} \cos\theta \sin\theta d\theta$$

$$= \pi R^2 n_o \left[-\cos^2\theta\right]_{0^\circ}^{90^\circ} = \pi R^2 n_o \left[\frac{\pi}{4}\right]$$

Therefore, the total number of photons leaving a given source area each second is equal to,

$$N = \frac{\pi^2 R^2 n_o}{4}$$

Solving for n we see that the number of photons per unit area per second entering a given aperture is equal to,

$$n = \frac{4N\cos\theta}{\pi^2 R^2}$$

APPENDIX C

LINE SCAN SYSTEM

This portion of the VOIS unit which accomplishes the cartographic mapping function, must be designed to provide the best possible resolution within the restrictions imposed by transmission bandwidth and total available mapping time. If we assume that low resolution mapping is done in "real time" and observe that the time available for transmission is greater than that required for mapping, then the transmission bandwidth is the controlling factor in the determination of the size of the smallest resolvable element.

Therefore, for a line scan system,

$$\text{transmission bandwidth} = \frac{\text{elements}}{\text{scan line}} \times \frac{\text{scan lines}}{\text{second}} .$$

No correction is made for the fact that one sinusoid equals two elements. However since topographic coverage is required, each element (e) is considered to be one "stereo" element.

The number of elements per scan line is equal to

$$n = \frac{W}{e}$$

where

W = the strip width in meters

and

e = element size in meters

The scan rate in lines per second is a function of the required line spacing upon the lunar surface and the time required for a single pass of the vehicle. Therefore, the number of lines per second is equal to

$$L = \frac{1/2\ C_m K}{1/2\ Te}$$

Where

K = the Kell factor which equals the number of scan lines per resolvable element

C_m = the lunar circumference in meters

T = the orbital period in seconds

and

e = element in meters

Therefore, the transmission bandwidth is equal to

$$f = \frac{1/2\ WC_m K}{1/2\ Te^2} = \frac{WC_m K}{Te^2}$$

and the element size becomes

$$e = \sqrt{\frac{WC_mK}{Tf}}$$

For an orbital altitude of 100 KM,

$$W = 40{,}000 \text{ meters}$$

$$T = 118.3 \text{ minutes} = 7096 \text{ seconds}$$

and

$$C_m = 10910 \times 10^3 \text{ meters}$$

$$f = 10^6 \text{ CPS}$$

$$K = 1.4$$

APPENDIX D

THE MAPPING PROBLEM

A terrestrial map is a plane representation at reduced scale of part or whole of the earth's surface. Since a similar definition will apply to lunar maps, martian maps et al ... one may conclude that maps will have the same essential properties regardless of the areas they represent and as such the term map can be uniquivocally applied throughout the universe. One may further assert that the established and well-known methods for producing terrestrial maps are equally useful for mapping anywhere. It should be noted, however, that specific maps differ greatly not only as to the scale and accuracy at which they are drawn, but also with respect to their content density or the type of information represented.

Differences of accuracy and content are the derivatives of the particular methods used in constructing the map. Since the science of map making is one of the older sciences, there should be very little difficulty selecting the particular ground data reduction methods which will permit the desired results to be obtained. On the other hand, it is important to recognize that an efficiently organized ground mapping system can only be developed after thorough analysis of the existing alternatives. Current advances in the state of the art in mapping raw data collection techniques plus ground data reduction and map production, especially in areas utilizing electronic computers for analysis of mapping problems, open vast new avenues of approach to conventional map compilation problems. It is recognized that a detailed analysis of ground data reduction techniques as applied to the lunar cartographic problem is outside the scope of this study. However, cognizance must be taken of general mapping requirements and procedures in order that VOIS designs reflect good mapping practice compatible with overall system objectives. It is pertinent to suggest, therefore, immediate instigation of such a study not only for the reasons mentioned but also to provide guidance toward more effective assignment of functions to the collection system and the ground data reduction system.

Of the techniques which may be employed to produce lunar maps, the method of observation and recording underlies and fixes the limits for all. It is important, therefore, to vary the observation methods according to the purpose of the observations. Similarly, the observation and data collection plan should be focused upon reliability within practical limits rather than ultimate limits. It is more than fortuitous for example, that the J.P.L. proposed VOIS package utilizes two different recording systems, one to record completely the metric cartographic information, the other to observe more detailed information in selected areas. With this system, a plan for information accumulation can utilize a collection flexibility which may be varied according to purpose and yet each of the sub-systems can operate within well established practical limits. Utilization of this type of flexibility gives the system both functional reliability and long term selectivity which, in principle at least, should extend its useful life as a fundamental design.

For centuries, map making systems have focused attention on the metric character of the observations. The reasons of course are obvious, considering the geometric relationships between the features to be represented and the specific type of information to be conveyed. Less obvious perhaps is the tremendous gain in efficiency obtained by reducing ambiguities in the data with high stability in recording.

It is a well accepted fact that low accuracy maps become obsolete much sooner than high accuracy maps. Moreover, extensive revisions of poorly prepared map bases are very costly and in the end often do not produce the desired result. Consequently, when poor quality maps need revision, the established practice is to remap, meeting the new standards desired. Therefore, in the long run preparation of a high quality map, to begin with, is cheaper than successive approximations.

Most important of the quality considerations to be made for a base map series, is the geometric fidelity. Geometric fidelity, once obtained to acceptable standards, permits economical revision and updating. Accordingly, it is most important that the lunar orbiter recording and readout systems provide the best geometric fidelity possible. If the geometric relationships are "frozen" at the instant of exposure in a form which permits their subsequent recovery, succeeding processing steps need not degrade the metric relationships significantly.

Fairchild-Du Mont has been particularly sensitive to this problem in the design of their system. The fiducial position of each fiber in the VOIS camera effectively establishes a metric relationship at the instant of exposure, permitting precise reconstruction of the spatial relationships between object and image.

Mapping the surface of the moon is analogous to many other scientific problems. More specifically, the production of lunar maps should proceed in accordance with established scientific prinicples and techniques for observation and accumulation of data and for its orderly classification and correlation. Any other approach may result in an overabundance of map data in the sense that no orderly classification or correlation is possible and the maps produced will be non-continguous and of heterogenous quality.

There are numerous examples of overabundant and ambiguous data in the history of earth mapping such as local data, special purpose surveys, incompatible scales and so forth. Mapping all of the moon, using an artifical satellite will be accomplished with great speed as compared to classical earth mapping. It is, therefore, essential to have a well developed lunar mapping plan which integrates not only the immediate and long range mapping requirements per se, but a plan which is consonant with all of man's expected activities on or near the surface of the moon.

The specific lunar mapping requirements may be divided into immediate and long range in terms of accuracy, speed and content. For example, varying degrees of accuracy, speed and content are needed for different purposes as these purposes relate to the development of specific activities in an area. Therefore, it is fundamentally important to develop, first of all, an homogeneous mapping framework for the entire surface of the moon and then fill in details related to specific user requirements.

There are map data requirements which include accuracy, speed and content related to real time needs such as, programming or re-programming of orbiting collection systems. In addition, there are needs to generate map data as a basis for planning future probes. Moreover, there are immediate and long range requirements for establishing a standard map series framework which satisfies the early collection needs and yet provides the geographic index for all future observations of the moon.

The first consideration in developing an homogeneous cartographic framework for the lunar surface is the shape of the moon itself. This problem will be the concern of the geodesists who will develop the mathematical model for the surface so that each lunar feature may be unambiguously referenced to all other features.

A best fit to the lunar mathematical model is essentially a cartographic problem. Use of advanced photogrammetric analysis and measurement techniques will be required but it is not anticipated that any new methods need be developed. The quantities observed by the VOIS system for the most part will be continuous. However, due to planned techniques of recording, communications, and storage, data may be initially available to the analysts in a non-continuous form. A conventional terrestrial example of this is the use of overlapping frame photography in mapping. The earth surface is continuous, the photographs are discreet samples that must be tied together to restore the continuous area. This type of problem has been solved in existing photographic survey systems. Proper restitution is accomplished by utilizing redundant coverage for interdependent observation in order to recover satisfactory continuity. The accuracy of the maps that result from this process are dependent, of course, upon the fidelity of the accomplishment, as mentioned previously. Presumably, the map scales selected for actual map compilation can be established after receipt of real inputs when the geometric fidelity of the reassembled record is better known. To give some idea of the bases for map scale selection a table of the more quantitative map design parameters is given.

Table D.1 lists the nominal parameters associated with map design. The parameters listed are graphical map limits and as such demonstrate only what could be represented at the various mapping scales. From a table such as table D.2, the photographic system can be designed to meet specific mapping requirements or once given a specific photographic system of calibrated resolution and precision, one can select an optimum range of mapping scales related to photographic scale and photographic fidelity. To satisfy immediate and long range goals, it may be necessary to select two or more map scales in terms of particular requirements or in terms of the properties of the collected observations.

Generally, there are two classes of maps, namely planning and operational maps. These classifications are valid generally but the scales used for different applications are as varied as the applications. For example, civil engineering construction planning maps and aircraft flight engineering planning maps are both planning maps, but they differ in scales and content. Since scale and content variations for different purposes are numerous and, a priori, not always explicit, it is essential to develop a general series of map scales and content characteristics and then, fill in as required with special purpose maps. This in fact is what has been done in most of the countries of the world including the United States. Presumably, this will done for the moon.

The United States National Standards of Map Accuracy require a horizontal accuracy such that for maps published at 1:20,000 scale and smaller, (1:20,000 scale is 1-inch equals 1,670 feet) not more than 10% of the well defined features, shall be in error by more than 1/50-inch. Similarly, the vertical accuracy tolerance, as applied to contour maps at all publication scales, shall be such that not more than 10% of the elevations tested shall be in error by more than 1/2 the contour interval. The National Standards also state that the accuracy of any map may be tested using positions and elevations determined by a survey of higher accuracy. Despite the fact that the lunar mapping conditions are not the same, we can assume that these standards represent a practical goal for lunar mapping.

While it is desirable to utilize the existing standards for map accuracy, the conditions for testing lunar map accuracies are likely to be considerably different than terrestrial accuracy testing. It is, therefore, desirable to convert the United States Standards to a statistical equivalent which then gives some mathematical basis for lunar map standards and perhaps a better basis for lunar map testing. Fortunately, it is a simple matter to convert the existing United States criteria to statistical equivalents in terms of standard error Using redundant observation and various statistical techniques to determine standard deviation and variance, it is possible to establish analytical standards for lunar map accuracy. For horizontal accuracy at 90% within 1/50-inch the converted equivalent standard error would be:

$$\rho_h = \frac{0.02''}{1.66}$$

$$\rho_h = 0.012''$$

in inches at the map scale.

The vertical tolerance of 1/2 contour interval for 90% of the contours in equivalent standard error would be:

$$\rho_v = \frac{1/2\ \text{C.I.}}{1.66} + \rho_h \text{ tan angle of slope}$$

$$\rho_v = 0.3\ \text{C.I.} + 0.012\ t$$

where ρ_h = horizontal standard error at the map scale

ρ_v = vertical standard error at the map scale

C.I. = contour interval at the map scale

t = tan of ground slope angle

For example, applying this equivalent standard to lunar maps at a scale of 1:500,000, a possible scale with 10 meter resolution sensors showing 50 meter contours the horizontal and vertical standard error tolerances would be:

$$\rho_h = \frac{.02 \times 25.4 \times 500{,}000}{1.66}$$

$$\rho_h = 165 \text{ meters}$$

and,

$$\rho_v = 0.3 \times 50 + 165t$$

$$\rho_v = 15 + 165t$$

$$\rho_v = 15 \text{ meters} + \text{horizontal tolerance} \times \text{tangent angle of slope}$$

Table D.2 lists the various precision factors which could be utilized to select precision compatible with standard error tolerances at specific mapping scales and contour intervals. Stereo-photogrammetic mapping accuracy can be expressed as a function of photographic resolution, photographic scale, the perspective angle of convergence (stereo angle) and the final map scale. See Figure D.1 and D.2 for examples of stereo-type collection systems. To assess only the maximum photographic accuracies obtainable in the VOIS system we can ignore the final map scale since final map accuracy limits are listed in Table D.1.

Resolution is defined as the smallest resolvable ground element.

Convergence angle is defined as the angle formed by the distance between successive camera node positions, and the height of the camera node a above the nadir point (Base/Height = tan angle of convergence).

Scale is defined as focal length divided by the height of the camera node above the object plane. (All photographs have a multiplicity of scales depending upon camera attitude at exposure. The photographic scale used herein and represented by f/H is the nominal photographic scale in a vertical photograph.)

If one converts the imaging resolution elements to meters on the lunar surface by the use of nominal scale factors, a table of photographic horizontal and vertical precision can be made in terms of lunar ground resolution and base-height ratios. See Table D.2. This table is only representative of the precision of independent observations on stereoscopic photographs. It is useful because it represents the limits for maximum mapping accuracy in terms of anticipated resolutions. Practical accuracies will be 5 to 10 times the errors shown for individual observations when considered with respect to the lunar datum as a continuous quantity.

The content and type of map produced will depend not only upon the accuracy obtainable but also upon the user requirements. Fundamental to all specialized requirements, however, will be the geographic index provided for all applications at various levels of detail. This index will serve as the framework tabulating, storing and retrieving all lunar data.

The surface of the moon is approximately one fourth of the land area surface of the earth. (Earth land area 159×10^{12} meters^2- Moon area 38×10^{12} meters^2) The map contents will reflect the specialized requirements of geologists, geophysicists, navigators, etc. This merely further emphasizes the need to properly classify, index, compile and store all collected data in terms of subject and geographic coordinates. Moreover, it surely points up the requirement to remove all ambiguities in geographic position so that ambiguities in content do not occur.

There are two forms for presenting map data. One is tabular, where the objects or features are described in documentary form and associated with a numerical tabulation of the individual feature coordinate position. The other is graphic, in either line map or photo map form, using various degrees of symbolic and name descriptions. To satisfy high speed requirements, map data is usually produced in tabular form as a digital output from a measurement process. In the tabular case, the only transformations made are mathematical. Graphics require physical transformations and, therefore, are produced at lower speed. It is essential to note, however, that tabular map data are limited to selected features at a density usually much lower than the system resolution, whereas the graphic map data can be presented at information densities equivalent to the system resolution.

It appears obvious then that the high speed response requirements will be satisfied by reducing data for selected features only and presenting the outputs in tabular form. For these type of outputs, it is certainly reasonable to expect that selected feature map data can be output within two hours of the receipt of input data. To accomplish the high speed data reduction automated viewers connected to a computer facility will be required. These high speed viewers will have to be rather sophisticated devices, capable of real time operation and supported by real time computation facilities. The major design parameters for such viewers are:

1. Precise and rapid measurement
2. Magnification
3. Resolution
4. Screen spatial line frequency
5. Brightness
6. Brightness uniformity
7. Screen gain fall-off
8. Screen contrast
9. Screen size
10. Viewing distance
11. Visual input density range
12. Ambient luminance levels.

The output of these special real time devices would be tabular map type data.

For graphic products such as topographic maps, photo-mosaics, navigational charts, etc., the time required to produce the final map product is nominally dependent upon the relationship between the photographic scale and the final map scale. As a rule of thumb, however, it has been found that for line map compilation, the photo compiler uses about one-half hour per square inch of photograph. In the experience aggregate, there is about a one to one correspondence between the time the photo compiler uses and the time to perform the other physical transformations when the map scale is the same as the photo scale. Similarly, the time to produce the final map varies with the difference between photo scale and final map scale as a function of magnification. See Figure D.3. It is apparent that at scales larger than photo scale, the time to produce the final map increases in accordance with the relationship

$$T_{pc} \quad (1 \; m) \quad = \quad T_{map}$$

where

T_{pc} = Photo Compilation Time per square inch of photo

m = Magnification between photo scale and map scale

T_{map} = Total map completion time

To maximize production speeds, the smallest acceptable map scale should be used. However, the most efficient utilization of the recorded images will depend upon the proper relationship between what is recorded on the photograph and what is needed on the map.

SCALE	LUNAR MAP DESIGN PARAMETERS								
	[illegible]	1:[illegible]	1:100,000	1:200,000	1:400,000	1:800,000	1:1,600,000	1:3,200,000	1:6,400,000
Number of Sq. KM per Map Sheet	[illegible]	[illegible]	10,000	40,000	160,000	640,000	2,560,000	10,240,000	40,960,000
Approx. No. of map sheets to cover moon	[illegible]	15,200	3,800	950	238	60	15	4	1
Minimum size ground feature in meters [illegible]	25	50	100	200	400	800	1,600	3,200	6,400
Minimum size "Landmark" feature in meters symbolized at 5x true scal	[illegible]	10	20	40	80	160	320	640	1,280
Minimum Graphical Contour Interval in [illegible] of slope (in meters) at 10% slope	1.875	[illegible]	7.5	15.	30.	60.	120.	240.	480.
" at 20% slope	[illegible]	7.5	15.	30.	60.	120.	240.	480.	960.
" at 30% slope	[illegible]	[illegible]	22.50	45.	90.	180.	360.	720.	[illegible]
" at 40% slope	[illegible]	[illegible]	30	60.	120.	240.	480.	960.	1,920.
" at 50% slope	[illegible]	[illegible]	37.50	75.	150.	300.	600.	1,200.	2,400.
Maximum Graphical Planimetric Accuracy for 90% of Features	[illegible]	[illegible]	[illegible]	100.	200.	400.	800.	1,600.	3,200.
Maximum Graphical Topographic Accuracy for 90% of contours at 10% slope	[illegible]	[illegible]	[illegible]	[illegible]	20.0	40.0	80.0	160.0	320.0
" at 20% slope	[illegible]	[illegible]	10.0	20.0	40.0	80.0	160.0	320.0	640.0
" at 30% slope	[illegible]	7.5	15.0	30.0	60.0	120.0	240.0	480.0	960.0
" at 40% slope	5.0	[illegible]	20.	40.	80.0	160.	320.	640.	1,280.
" at 50% slope	6.25	12.5	25.	50.	100.	200.	400.	800.	1,600.

TABLE D-1

PHOTOGRAPHIC RESOLUTION IN METERS		1 METER HORIZ.	1 METER VERT.	5 METERS H	5 METERS V	10 METERS H	10 METERS V	20 METERS H	20 METERS V
PRECISION IN METERS WHEN B/H	= 1.5	1.803	.66667	9.015	3.3333	18.03	6.6667	36.6	13.333
	= 1.4	1.7205	.714286	8.603	3.57143	17.205	7.14286	34.41	14.286
	= 1.3	1.6401	.769231	8.2005	3.8462	16.401	7.69231	32.802	15.3846
	= 1.2	1.5621	.83333	7.8105	4.16666	15.621	8.333	31.242	16.6666
	= 1.1	1.487	.909091	7.435	4.54545	14.87	9.0909	29.74	18.1818
	= 1.0	1.414	1.0	7.07	5.0	14.14	10.0	28.28	20.0
	= .9	1.3454	1.11111	6.727	5.5555	13.454	11.1111	26.908	22.2222
	= .8	1.2806	1.25	6.403	6.25	12.806	12.5	25.612	25.000
	= .7	1.2207	1.4286	6.1035	7.143	12.207	14.286	24.414	28.572
	= .6	1.1662	1.66667	5.8310	8.333	11.662	16.6667	23.304	33.3333
	= .5	1.1180	2.0	5.59	10	11.180	20.	22.36	40.000
	= .4	1.077	2.5	5.385	12.5	10.77	25.	21.54	50.000
	= .3	1.044	3.3333	5.22	16.66667	10.44	33.3333	20.88	66.6666
	= .2	1.0198	5.0	5.099	25.00	10.198	50.00	20.396	100.00
	= .1	1.005	10.0	5.025	50.0	10.05	100.000	20.10	200.00
REQUIRED BANDWIDTH TO TRANSMIT LUNAR SURFACE FOR STEREO MAPPING		100MC		4MC		1MC		250KC	

PHOTOGRAPHIC RESOLUTION IN METERS		30 METERS H	30 METERS V	50 METERS H	50 METERS V	100 METERS H	100 METERS V
PRECISION IN METERS WHEN B/H	= 1.5	54.09	20.0	90.5	33.333	180.3	66.667
	= 1.4	51.615	21.429	86.03	35.7143	172.05	71.4286
	= 1.3	49.203	23.077	82.005	38.462	164.01	76.9231
	= 1.2	48.863	24.999	78.105	41.6666	156.21	83.333
	= 1.1	44.61	27.2727	74.35	45.4545	148.7	90.909
	= 1.0	42.42	30.00	70.7	50.0	141.4	100.00
	= .9	40.362	33.333	67.27	55.5555	134.54	111.111
	= .8	38.418	37.5	64.03	62.5	128.06	125.50
	= .7	36.621	42.858	61.035	71.43	122.07	142.86
	= .6	34.986	50.00	58.310	83.33	116.62	166.667
	= .5	33.54	60.00	55.9	100.00	111.80	200.00
	= .4	32.31	75.00	53.85	125.00	107.7	250.00
	= .3	31.32	100.00	52.20	166.6667	104.4	333.333
	= .2	30.594	150.00	50.99	250.00	101.98	500.000
	= .1	30.15	300.00	50.25	500.00	100.5	1000.000
REQUIRED BANDWIDTH TO TRANSMIT LUNAR SURFACE FOR STEREO MAPPING		111KC		40KC		10KC	

TABLE D-2 PHOTOGRAPHIC PRECISION IN TERMS OF RESOLUTION

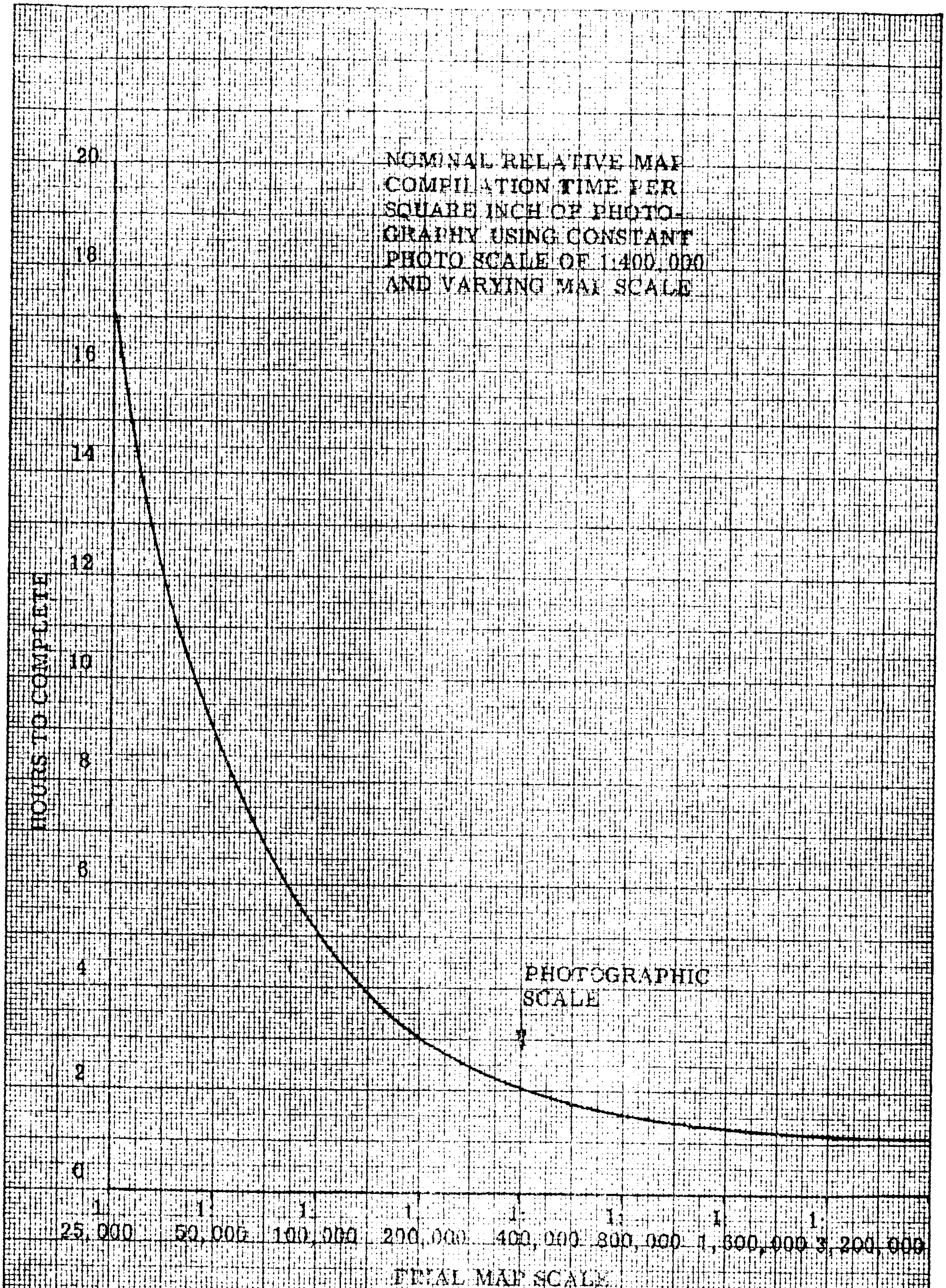
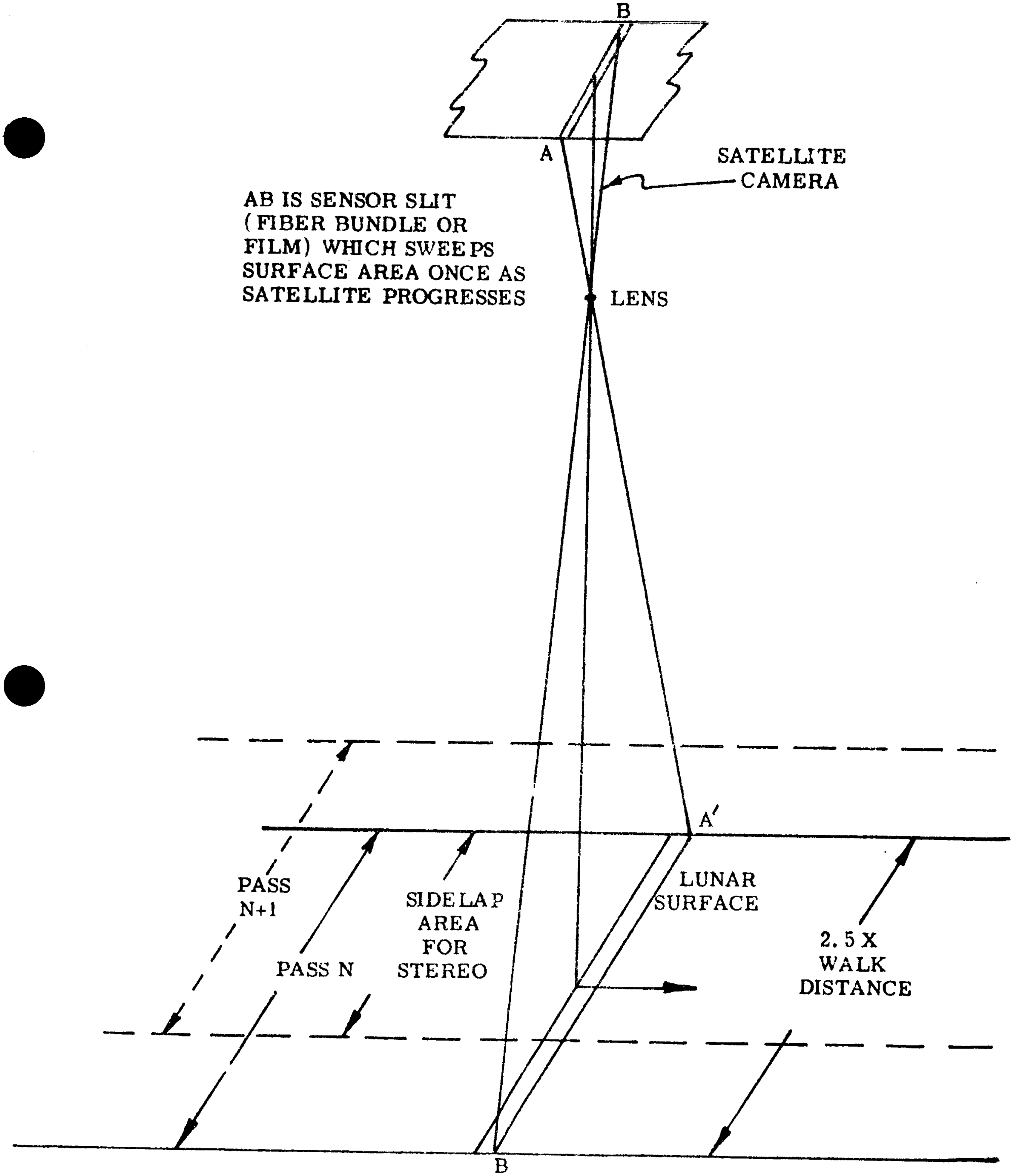
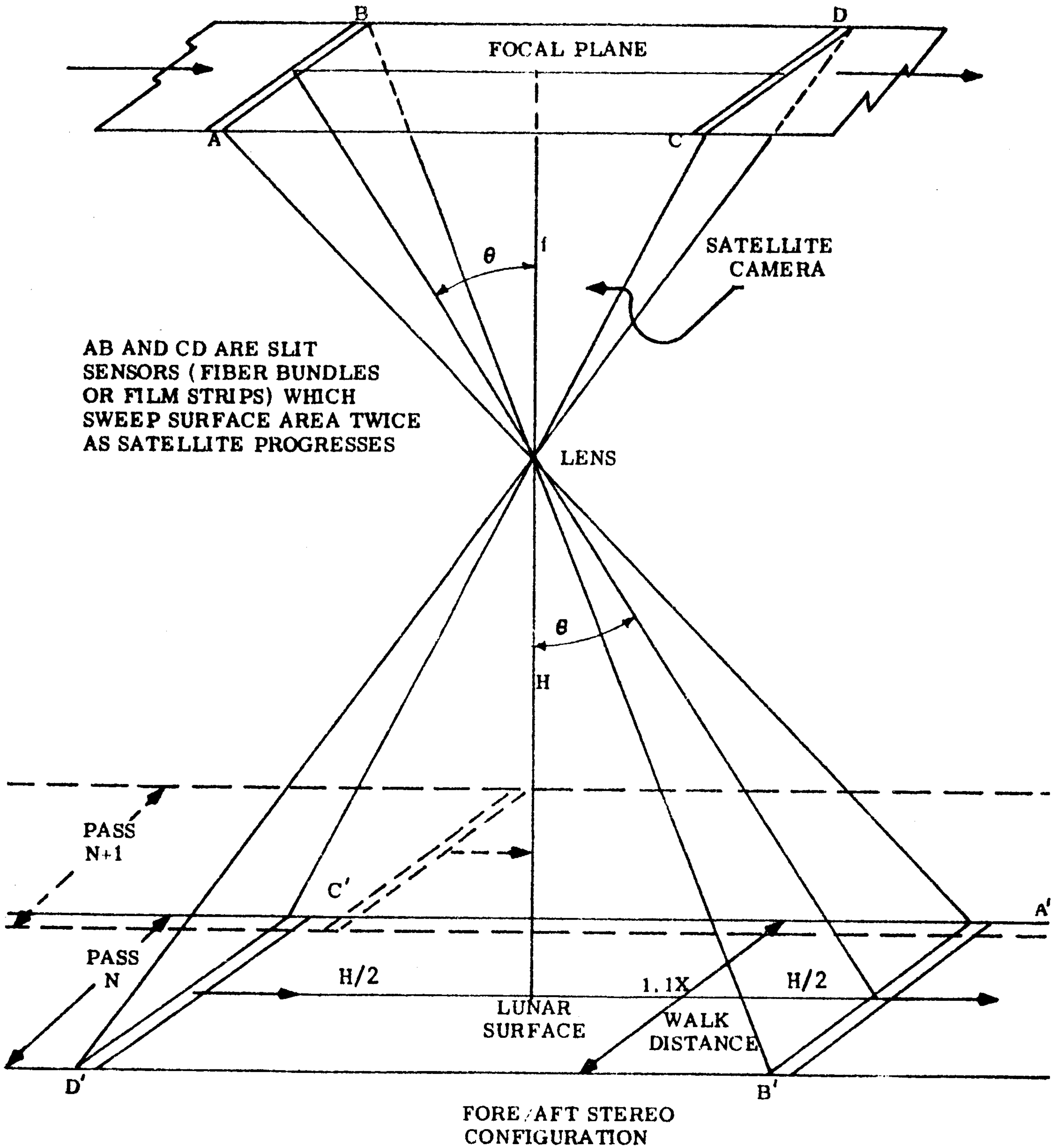

NOMINAL RELATIVE MAP
COMPILATION TIME PER
SQUARE INCH OF PHOTO-
GRAPHY USING CONSTANT
PHOTO SCALE OF 1:400,000
AND VARYING MAP SCALE
HOURS TO COMPLETE
20
18
16
14
12
10
8
6
4
2
0
PHOTOGRAPHIC
SCALE
1 / 25,000
1 / 50,000
1 / 100,000
1 / 200,000
1 / 400,000
1 / 800,000
1 / 1,600,000
1 / 3,200,000
FINAL MAP SCALE

TABLE D-3



SIDELAP STEREO CONFIGURATION

FIGURE D-1



B
D
FOCAL PLANE
A
C
θ
f
SATELLITE
CAMERA
AB AND CD ARE SLIT
SENSORS (FIBER BUNDLES
OR FILM STRIPS) WHICH
SWEEP SURFACE AREA TWICE
AS SATELLITE PROGRESSES
LENS
θ
H
PASS
N+1
C'
A'
PASS
N
H/2
1.1X
H/2
LUNAR
SURFACE
WALK
DISTANCE
D'
B'
FORE/AFT STEREO
CONFIGURATION

FIGURE D-2

APPENDIX E

ORBITAL GEOMETRY AND SUB-SYSTEM OPERATION SCHEDULE

A. Satellite Motion

It has been found from the work of H. Lass(1),(2), as well as subsequent work based on a less simplified picture of lunar orbital configurations(3) that approximately circular polar lunar satellite orbits remain essentially parallel to themselves for several months. Since this is the type of orbit under consideration, a constant orientation of the satellite orbital plane (with respect to an inertial frame) will be assumed in the discussions that follow.

B. Flight Schedule

In order to observe both polar regions of the moon while these are illuminated by the sun, the mid-point of the observation month should be chosen to be no more than about a week from the time of lunar equinox. To illustrate, January 20, 1963

(1) H. Lass, The Motion of a Satellite of the Moon, Jet Propulsion Lab., California Inst. Tech., Pasadena, California, April 1960.
(2) H. Lass, Carlton B. Solloway, The Motion of a Satellite of the Moon, Jet Propulsion Lab., Pasadena, California, 1960.
(3) Lass does not include the fact that the rotation axis of the moon and its orbital revolution axis make an angle of about 6.5° with each other, but in effect treats the problem as if the angle were 0°. When the 6.5° angle is taken into account, however, his original conclusions are found, for all practical purposes, still to be valid.

is a time of lunar equinox, while January 24, 1963 is a time of new moon. Let us, for example, choose the mid-point to occur on January 24, 1963.

Further, the orbital plane of the satellite may be oriented so that it includes the sun on January 24. Since January 24 is a time of new moon, it follows that the satellite orbital plane is normal to the plane of the lunar night-day (terminator) circle. While it is not necessary that these planes be precisely perpendicular, it is desirable that they do not deviate by more than say 30° from normal, since large regions observed by the satellite would otherwise be receiving only grazing solar illumination.

The beginning of the observation month occurs half a sidereal month before January 24, or on January 10. For the satellite orbital plane orientation above designated, the sun will at this time lie approximately 14° off the satellite orbital plane. At the conclusion of the mapping month, the sun will lie 14° off in the opposite direction. Thus, at no time during the mapping will the satellite orbital plane deviate from the normal to the plane of the terminator circle by more than $\pm 14°$.

The beginning of the mapping period, January 10, occurs within one day after full moon. For the satellite orbital plane orientation considered, launching into the selenocentric orbit near the time of full moon is desirable from the viewpoint of minimum fuel expenditure.

C. Line of Sight Contact of Satellite with Earth

The occultation and reappearance times of the satellite as seen by an observer on earth are determined by the satellite flight schedule. To solve for these times, we proceed as follows:

A circular satellite orbit of a specified height, and having a specified orientation of its plane with respect to the lunar orbital plane above the earth is considered. Then we may determine, for any given angular location θ of the moon in its orbit about the earth, the two "end-points" on the "local satellite orbit circle" between which part of the orbit circle is hidden from an observer on the earth. These points are specified as having phases ϕ_A and ϕ_B on the satellite orbit circle. For brevity either end-point ϕ_A or ϕ_B will be represented by the common symbol ϕ_E.

According to the specific satellite flight schedule, there will be times at which one of these two points (the locations of which are determined according to the instantaneous value of θ) coincides with the location of the satellite at that moment. This coincidence point represents an appearance or occultation of the satellite. The problem may then be regarded as one of solving simultaneously the expression for the satellite orbit circle end-points $\phi_E(\theta)$ with the expression for the satellite location in its orbit, denoted by $\phi(\theta)$. (As in the case of the satellite orbital circle end-points, designated by their satellite orbit phase locations ϕ_E, we designate the location of the satellite in its orbit, by its phase angle, ϕ).

It is desired to find the satellite appearance and occultation points as functions of time, rather than as functions of θ. To do this, we first express time t as a function of θ. Then we in effect eliminate θ between $t(\theta)$ and the previously found $\phi_E(\theta)$ to get $\phi_E(t)$. (In computer terms, θ is printed out along with the corresponding $\phi_E(\theta)$ and $t(\theta)$ values.)

Having $\phi_E(t)$, the location of the satellite is now expressed in terms of its orbital phase angle $\phi(t)$. Because of the assumed circular motion of the satellite, $\phi(t)$ is a simple linear (sawtooth) expression [though $\phi(\theta)$, which would have been the function to be used if we had solved $\phi_E(\theta)$ simultaneously with $\phi(\theta)$, is a complicated expression]. The functions $\phi_E(t)$ and $\phi(t)$ may be solved simultaneously to get coincidence points ($\phi_{coinc.}$, $t_{coinc.}$), which are the satellite occultation and appearance phases and times. In the example here considered this last step will be done graphically - ie - the curves $\phi_E(t)$ and $\phi(t)$ will be plotted, their intersections being the points ($\phi_{coinc.}$, $t_{coinc.}$).

In solving the above problem of finding the occultation and appearance times of the satellite $t_{coinc.}$, it was necessary to find $t(\theta)$. To find $t(\theta)$, we may for the present purposes assume this to be a two-body problem (earth-moon system only, neglecting the sun, as well as earth non-sphericalness, etc). Actually the major axis of the elliptical orbit of the moon rotates about 3° during the observation month, which would not be the case in an ideal two body problem; but as a result of the lunar orbit eccentricity not being excessive, this may be neglected. Similarly, other perturbation effects, such as regression of the line of nodes, variation of inclination of the lunar orbital plane to the ecliptic, etc., are not included.

While $t(\theta)$ may be expressed in closed form in the case of classical two body elliptical motion, the result is quite complicated (unlike relating θ to the radius vector $\mathcal{r}$, which is simple). It is more convenient, from the viewpoint of computer programming, to express $t(\theta)$ by a series approximation.

Corresponding to the example considered in paragraph B, the moon's orbit ellipse about the earth will have the following characteristics on January 24, 1963: The apogee line will be 199° east (approximately along the ecliptic) from the (earth's) vernal equinox. The radius vector from the earth to the moon will be 76° west of the apogee line along the lunar orbit. Further, in paragraph B, the satellite orbital plane was oriented so as to contain the radius vector from the earth to the moon on January 24. For the present illustrative numerical determination of satellite occultation and appearance times, we will, in addition to the foregoing, assume the following nominal parameters: The lunar orbit eccentricity is taken to be .0549. The angle between the lunar rotation axis and its orbital revolution axis is taken to be 6.5°, the rotation axis of this angle being assumed to be the radius vector from the sun to the earth (which is approximately so at the time of lunar equinox).

A program for the IBM-1620 computer has been set up to determine the satellite occultation and appearance times using the approach outlined above. Numerical results and graphs are being prepared.

D. Time During Which Satellite is Above Sun-Illuminated Lunar Surface and Time During Which Satellite is Directly Illuminated by the Sun.

The methods for determining these times are considerally simpler than the above discussed line of sight problem and will not be described here. Instead, we will merely cite the essential results for the case of the above assumed flight program, in which the satellite orbital plane is normal to the plane of the plane of the terminator circle at the center of the observation month.

It is found that the satellite will be over regions directly illuminated by sunlight for very nearly uniformly spaced intervals throughout the month. Specifically, the maximum variation in the center point of a passage over the illuminated region occurs between the beginning and end of the observation month, and constitutes only a .8° total shift in the phase of the satellite orbit. This corresponds to a 15 mile total shift along the lunar surface. The variation throughout the observation month in length of the intervals over the illuminated region (which constitute approximately 180° of satellite orbit angle) is very nearly zero. (It would be precisely zero if the sun were a point source at infinity, the moon were a perfect sphere, and the moon did not move with respect to the sun; e.g., as it follows the earth in the motion of the latter around the sun.) For practical computation purposes in determining a typical satellite mapping operation schedule, the variation in the interval center points and lengths may be assumed to be zero.

The intervals and centers of the intervals during which the satellite receives direct sunlight are found generally to vary only slightly over the observation month, though these are larger than the corresponding variations in the preceding paragraph, and moveover depend upon the orbit height. For a 100 Km high orbit the maximum variation during the observation month of the center point of a passage through direct sunlight is about 1.3° of phase in the orbit circle. This represents a shift of this center along the orbit circle of about 25 miles. The variation in length of the satellite orbit arc which is in direct sunlight is less. For practical purposes in determining a typical satellite operation schedule this variation is quite negligible - that is, complete repeatability, in terms of satellite orbital phase, could be assumed throughout the observation month. In any case, the variation may be included if desired with no substantial complication of the computation problem.

E. Mapping Operation Schedule

Using the information obtained on line of sight time, satellite time over illuminated lunar surface and time during which the satellite receives direct sunlight, a typical mapping operation schedule, of the type described in the parametric study portion of this document, may be determined. Such a schedule is being prepared for the example above considered.

While a schedule of this type serves to describe a typical mapping operation, it would not be employed to actually preprogram such an operation. An attempt to preprogram a mapping operation appears impractical in that it would require a prior knowledge of the exact time the satellite was launched into a selenocentric orbit as well as of the precise satellite orbital parameters. In conjunction with these requirements, it would perhaps be necessary to use a less simplified description of lunar motion than was assumed here, though this latter condition can be met with no basic difficulty.